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FINAL REPORT
CIM 88/1 + SBIR-AF88-221
DESIGN PRODUCIBILITY ASSESSMENT SYSTEM

Contract No: F04704-88-C-0072

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DPAS is an engineering software tool that allows its users to calculate a number called the "Manufacturability Index" (MI). This number measures several design, material and manufacturing factors related to the level of product manufacturability. The assessment methodology assumes that the producibility assessment process is not a serial decision method, rather, it is a process with parallel interaction from origination of a conceptual design to direct linkage with design, manufacturing, and testing considerations. By formally establishing design rules and producibility criteria, DPAS provides an objective and unbiased producibility assessment judgement at any step in product development. This final report describes the Phase I research efforts with recommendations for a full scale program in Phase II.

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1. INTRODUCTION

This is the final report of CIM Systems' Phase I SBIR AF-88-221 (Contract No. F19628-88-C-0112 with the Ballistic Missile Office (BMO), Norton Air Force Base). The document describes research and defines requirements for developing a Design Producibility Assessment System (DPAS), that can be used to evaluate the producibility of hardware designs. The ultimate aim of this research initiative is the establishment of a foundation for development of a producibility assessment system, utilizing knowledge-based technologies. This will enable BMO's personnel to evaluate different types of hardware designs from a producibility perspective during or following product development. The Phase I effort has been directed toward reviewing and researching the technologies, and human reasoning processes that will be required in the development of this advanced support system. Metal parts have been the focus of Phase I research.

This report includes a conceptual design for DPAS for which an important aspect is its modularity. (Figure 1.1) The reason for providing this characteristic is the recognition that many of the producibility decisions and criteria will be studied independently before they are combined into a final system. Similarly, by structuring the reasoning process as presented, each knowledge source has a limited, well defined task which can be coordinated by a generalized heuristic. The system is designed to be highly configurable and easily customized to fit particular installation and producibility requirements. This feature is particularly significant because it will enable users to more easily integrate the system into their particular needs. From a user point of view, DPAS is a "friendly" system with menus, on-line help, on-line instructions and flexible user interfaces that will allow designers to perform "what if" queries. Through this capability, the user can modify design attributes and evaluate their impact on producibility.

The proposed system provides a full set of utilities for the initial definition update, and maintenance of the producibility assessment procedures, databases, and the various knowledge sources. The reason for providing this capability is the recognition that no one assessment procedure is universally accepted at this time. This flexibility will allow an easy conversion to new assessment procedures as they are developed. In addition, DPAS will be developed so that each organization attempting to use the system will not need a resident knowledge engineer to update the knowledge bases.

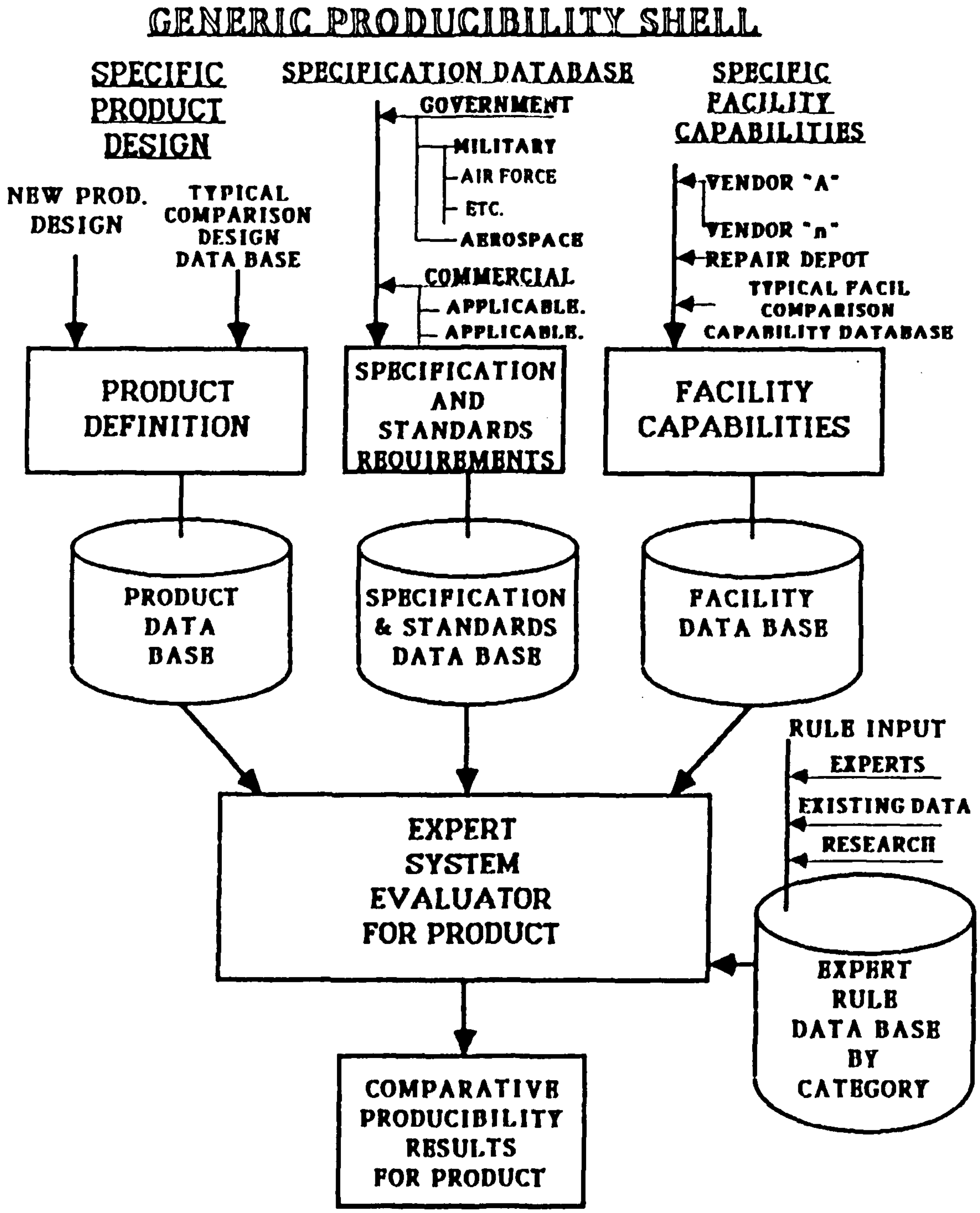

Figure 1.1. DPAS' Conceptual Overview.

2. CONCLUSIONS

The proposed DPAS system is an engineering software tool that allows the user to calculate a number called the "Manufacturability Index" (MI). This number measures several design, material and manufacturing factors related to the level of product manufacturability. Based on design characteristics, the system generates a relative measure of producibility before a design is complete. This capability allows the consideration of alternative design solutions.

Part of the Phase I effort has been devoted to the development of a decision network and criteria to represent the producibility assessment process. Data for this decisionmaking process is available but lacks organization. We have concluded that producibility information is very informally maintained and understood in most companies. The information often exists in only experienced personnel or in informal, off-line formats. DPAS will provide the capability to capture this data in an electronic form.

Because of the wide variety of hardware designs, it is infeasible to develop a single index which can be universally applied to each design type. Instead, an empirical approach has been selected to calculate the MI. An examination of a large number of metal components suggest that certain common factors can be quantified and combined by means of a simple formula to compute a relative metric of product manufacturability. The development team considered several alternatives for producibility assessment. (A brief discussion of some of these alternatives is presented in Appendix A.) For example, the manufacturing labor approach was rejected because its application requires that the design be completed in order to compute the amount of manufacturing labor required. This requirement makes difficult, if not impossible, to evaluate the manufacturability of a product at its early conceptual stage.

The research has demonstrated that a knowledge based approach is appropriate for measuring the producibility of a design. Therefore, the approach adopted in this project is the development of a producibility assessment system, which uses multiple expert knowledge sources to configure a knowledge-based system. The use of multiple knowledge sources simplifies the incremental construction of the system, a distinct advantage in developing a feasible production system. While several efforts to develop prototype producibility systems have been developed [Miller & Gogela 1972, Niebel 1966, Boothroyd 1986, Harry 1989], none of these efforts have used the multiple knowledge affecting producibility. A knowledge-based approach with multiple sources is considered to be an effective methodology.

One advantage of a knowledge-based approach over a conventional algorithmic method is the ability of the system to reason. For example, the design process used by a group of engineers and technicians usually consists of three stages: debate, negotiation, and conflict resolution. These kinds of processes can be dupli-

cated in a knowledge-based system where the reasoning processes that groups of people employ can be represented as strategies in the system.

A primary goal of the Phase II development effort will be to insure that the flexibility of the DPAS project accommodates the needs and long range planning of BMO. The potential savings and improvements in producibility made possible by this product should be of primary importance to the Air Force and other agencies in the Department of Defense. We feel the continuation of Phase II will provide considerable benefits specific to the DOD procurement of weapon systems and military hardware.

3. DPAS' FUNCTIONAL OVERVIEW

The DPAS system described in this document is structured to evaluate the producibility of different types of hardware designs. It is based on design, manufacturing, and testing experience and on our prototyping efforts.

An important feature of DPAS is that it is intended to be easily tailored (i.e. "boot-strapped") by the user organization. The system will provide a full set of utilities for the initial definition and maintenance for all the various knowledge sources. The reason for providing this flexibility is to insure that many of the producibility decisions and criteria will not require that each organization attempting to use it have a knowledge engineer to reprogram the knowledge bases. The modularization reflected in the knowledge sources is designed to make this "on-site" knowledge acquisition possible. By structuring the reasoning process, each knowledge source has a limited, well defined task. This allows the local expert to input his knowledge in a piecemeal fashion without being burdened by program control issues or communication with other parts of the knowledge base.

3.1 Producibility Assessment Categories. The proposed producibility assessment methodology includes the following main evaluation categories:

- Material selection and availability
- Commonality, simplification, and standardization
- Manufacturing process selection
- Features and tolerances
- Quality, inspection and tooling
- Assembly and systems considerations

The producibility items outlined in this section are just a sample of the many elements that will ultimately be combined to help form the producibility assessment rules of the DPAS' knowledge base. They represent isolated observations and although categorized, do not accurately represent the total number of categories or the total number of items within a given category. Every manufacturing industry, fabrication shop, designer or manufacturing expert has his own unique set of rules to operate by. Some of these unique rules may be inaccurate or even incorrect for other applications. Hence, the realization is that design rule collection, review, organization and definition is a significant effort which must be explicitly understood, to develop a fully functional system. Next is a brief description of the producibility assessment categories included in DPAS.

3.1.1 Material Selection and Availability. The selection of the right material for a new design is a vital step in the design

process. The appropriateness of the choice significantly impacts part performance, influences the selection of the manufacturing equipment, determines the manufacturing processes and affects other important producibility factors such as cost.

DPAS will have access to a knowledge base for materials in which a wide range of performance characteristics is available and to a database of currently available materials. In addition to traditional engineering properties such as physical and chemical, mechanical and geometric, others of importance such as material availability, standard sizes, property variability, cost and consumer appeal, etc. are also included. Considerations for producibility assessment will include, but will not be limited to the following factors:

- o Material criticality
  - New material with limited or no documentation or specs
  - Unique material difficult to get especially during wartime
  - Number of suppliers and foreign sources
  - Substitution and second sources
  - Lead time
- o Material availability in standard sizes and shapes
  - Flat stock
    - Plate
    - Sheet
    - Other: Screen, expanded metal, etc.
  - Bar stock
    - Round
    - Rectangular (includes square)
    - Hollow
    - Hex
    - Threaded rod
    - Other: Spline shaft, octagon, etc.
  - Tube stock
    - Round
    - Rectangular (includes square)
    - Other: Oval, etc.
  - Shapes
    - Engineering
      - Square angle
      - "U" Shaped
      - "T" Shaped
      - Other: F, M, Z, etc.
    - Structural
      - Angle
      - Channel
      - "H" Beam
      - "T" Shape

Rectangular (includes square)

- Special extrusions
- Forgings
- Billets

o Storage requirements such as ambient temperature and humidity/no controlled environment required

o Material properties such as alloy composition, strength, density, machinability, weldability, fatigue resistance, corrosion resistance, elongation and formability.

o Material handling such as commercial handling/special handling requirements

o Cost

o Material conditioning. Use-as-is without preconditioning.

o Material - Manufacturing process compatibility

o Hazardous features such as allergic, radiological, fire, and explosive factors.

3.1.2 Commonality, Standardization and Simplification. One of the greatest wastes of design engineering time and talent occurs when the "not designed here" *syndrome is in effect.* Designing a new product when an identical or similar product is already available is counter-productive. Where possible, previously designed parts or systems that meet the requirements should be used. For example, in mechanical engineering there are a number of standard parts such as bolts, nuts, etc. that are available from suppliers. A design for standardization rule is to design the product so that standard components are used as much as possible. Standardization and commonality considerations during design will allow the designer to maximize process repeatability, product inspectability, interchangeability, and product simplicity all of which are important factors for producibility.

Considerations for the producibility assessment of this category will include, but will not be limited to the following factors:

o The number of standard parts per assembly such as nuts, washers, bolts, screws, sprockets, and component combination.

o The number of different non-standard parts per assembly.

o The use of preferred numbers, sizes, scales, weights, raw materials near net shape, etc.

o The use of limits of fit, surface finish and tolerances

consistent with standards, testing procedures, and part function.

- The use of common available manufacturing processes, fixturing and tooling, alternative standard manufacturing processes.

- The number of standard/non-standard features per part.

- The number of interchangeable parts per assembly.

- The number of parts/final assembly.

- Simple and more producible design alternatives.

- Product modularity.

- The number of proprietary items or processes and manufacturing processes

- The number of different materials and manufacturing processes required to manufacture the final product.

- The number of non-standard manufacturing process alternatives.

3.1.3 Manufacturing Process Selection. The selection of the fabrication process needed to manufacture a product is a major parameter in producibility analysis. First, every manufacturing process is dependent on the type of material used. Every time that a designer selects a particular material to be used, indirectly he/she also specifies the methods of fabrication. For example, aluminum 356 is only available as a casting. Therefore, whenever this material is specified, the manufacturing process is specifically defined. Second, each manufacturing process is capable of meeting specific design requirements such as tolerances, surface finish, production quantity, and quality. For example, when a designer specifies very tight tolerances for a machined part only a few manufacturing processes can be selected. Third, the method of fabrication influences the total production cost, affects the production lead time, and the level of product quality. Consequently, the nature of the interrelation of the manufacturing method with other elements of the design process makes evident its consideration when designing for producibility. Some of the assessment factors that will be included in this category are listed below.

- Manufacturing technology. Production control, quality control systems, equipment adequacy, required labor skills.

- Manufacturing process availability. Availability, inadequate facilities such as restrictions to a single manufacturing process, design restrictions that prohibit certain common manufacturing process, design

not conducive to economic production, proprietary processes. Inadequate use of facilities such as line balancing, scheduling, facility planning, group technology, and critical resources.

- Manufacturing process efficiency. Achieved desired output, conserves material and energy, reduces waste.

- Effectiveness. Desired form, no changes introduced by production scale.

- Flexibility if the equipment is usable for more than one product/no dedicated situation.

- Manufacturing technology compatible with design without major changes.

- Manufacturing process alternatives. Availability of new or alternative planned manufacturing technology.

- Primary manufacturing process. Adequacy of primary manufacturing processes such as casting, forging, extrusion, drawing, and rolling to meet design requirements.

- Secondary manufacturing processes. Availability and appropriateness of manufacturing processes such as cutting, metal removal, shearing, finishing, etc., to meet design specifications.

- Availability and appropriateness of non-traditional secondary manufacturing processes such as electrical discharge machining, hydrodynamic machining, laser beam machining, etc.

- Production factors. Production batch size, material-manufacturing process compatibility, shape of the raw material, design geometry, maintenance programs, manufacturing methods, process planning, part size, shape and weight.

3.1.4 Features and Tolerances. Among the effects of design specifications on cost, those of geometric features, tolerances, and surface finish are perhaps the most significant factors. They affect the producibility of a new design in many ways from the need for additional manufacturing operations, to purchasing new high cost production equipment. This category includes the information that allows the designer to evaluate (i.e. trade-off) manufacturing difficulty for different geometric features.

A list of suggested producibility assessment factors should include, but not be limited to the following items:

- Product Basic Shape.

- Rotational component: Centric, concentric, gear-like.
- Non-rotational: Columnar, sheet form, prismatic, etc.

o Form Features.

- Chamfer, groove, thread, filler, notch, radius, etc.
- Hole, slot, cylindrical and plane surfaces.

o Design configuration and overdesigned/underdesigned features.

o Drawing specifications.

o Tolerances and surface finish specifications.

o Tolerance build up.

3.1.5 Quality, Inspection and Tooling. Quality, inspection, and tooling considerations are a major part of designing for producibility. An often used but accurate phrase is that "quality can not be inspected into a product but must be designed and built into it (Priest 1988)." In fact, quality and production requirements are closely related and mutually supportive. Another term closely related with quality is inspection. Inspection can be defined as a method, usually visual, of insuring that a manufacturing process has adequately taken place. Because tooling represents a sizable production investment, its influence in manufacturing has to be considered in order to minimize redundant tooling while maximizing design manufacturability.

The primary importance of tooling evaluation is the need for designing products that require minimum tooling and loading time. Parts which are complicated and difficult to handle or that require excessively intricate fixtures and tooling may need to be redesigned in view of its design characteristics. Some of the factors included in this assessment category are listed below:

o Manufacturing technology. Manufacturing process capabilities, product complexity, process planning, quality control, expected quality levels, production controls, material control, and manufacturing test concepts.

o Design requirements. Realistic tolerances and surface finish, quality assurance and design functions, control point charts, and the first article test specifications.

o Quality assurance. Sampling and inspection methods, selection of quality level (limiting quality, average outgoing quality, ...) cost of rework, and non-standard parts.

o Inspection and testing requirements, practical methods, equipment, non-destructive/destructive testing

techniques, proofing of functional items per operational procedures, test equipment, test points,

- Quality plan. Completed, approved, with qualification and inspection requirements.
- Quality system approved and in place.
- Quality considerations included earlier in the design phase.
- Quality awareness. Documented program/supported by top management.
- Standard tooling and test equipment integrated/not independent.
- Use of general purpose tooling.
- Design for inspection. Verifiable system and component inspection.
- Standard available/non-standard fixtures and tooling, cost, handling, set-up time, repair, tool design, tool proofing/certification.

3.1.6 Assembly and Systems Considerations. Since most of the product designs include some assembly requirements, one important segment of the cost of a product is its assembly cost. One way to reduce this portion of cost is to design products for ease of assembly. The issue of designing for assembly is considered in this project as a subset of the more general subject of producibility. This module stores data and design for assembly rules that measure the assemblability of a product. A basic rule used in this project is to design the components for easy automated assembly. If the product is easy to assemble by machine, it will be easy to assemble manually. Therefore, most of the design evaluations included in this section are related to automatic assembly. Below is a list of some of the assembly factors that should be included, but not limited to, in a producibility assessment review.

- Part function, design complexity, design standardization, and commonality.
- Tolerances, number of parts/assembly, modularity, motion or power wasted, tool clearances, component spacing, clearances for joining connectors, etc.
- Accessibility of parts during joining processes, fabrication constraints and assembly.
- Part function combination, type of mechanical fastener, design changes that improve assemblability.
- Type and availability of tooling (jigs and fixtures), and

fastener/cavity interface.

- Combining Components. Metal forming, casting, extrusion.
- Product Modularity.
- Assembly and Joining Techniques. Adhesive bonding, mechanical fastening (screws, threaded metal inserts, stamped metal screw receivers, drive pin fasteners, welding, etc.).
- Assembly Method, Process and Sequence. High-volume assembly considerations (work division, line balancing), assembly sequence for in-process inspection and repair.
- Total Assembly. Location points, vertical build assembly, single assembly operations, accessibility of important components, standardization and simplification, assembly tooling.
- Manpower assessment. Skill requirements match those available on hand; stability and training.
- Corporate knowledge. Published policies fully understood, kept current, developed for producibility programs.
- Integration of all functions from design to production.
- Packaging and maintenance considerations during preliminary design.

3.2 <u>The Producibility Assessment Methodology</u>. The proposed producibility assessment algorithm is a procedure where various problem-solving and decision-making techniques are used to determine product manufacturability. This approach requires the construction of a decision network and criteria that represent, as close as possible, the human reasoning requirements throughout a producibility assessment process as shown in Figure 3.1. This diagram is later used to create a taxonomy for the classification of the producibility evaluation rules and to calculate a relative index of producibility (simplicity/difficulty). The basic technical assumption of this method is that the producibility assessment process is not a serial decision method, rather, it is a process with parallel interactions from origination of a conceptual idea to direct linkage with a variety of producibility considerations. (Figure 3.1)

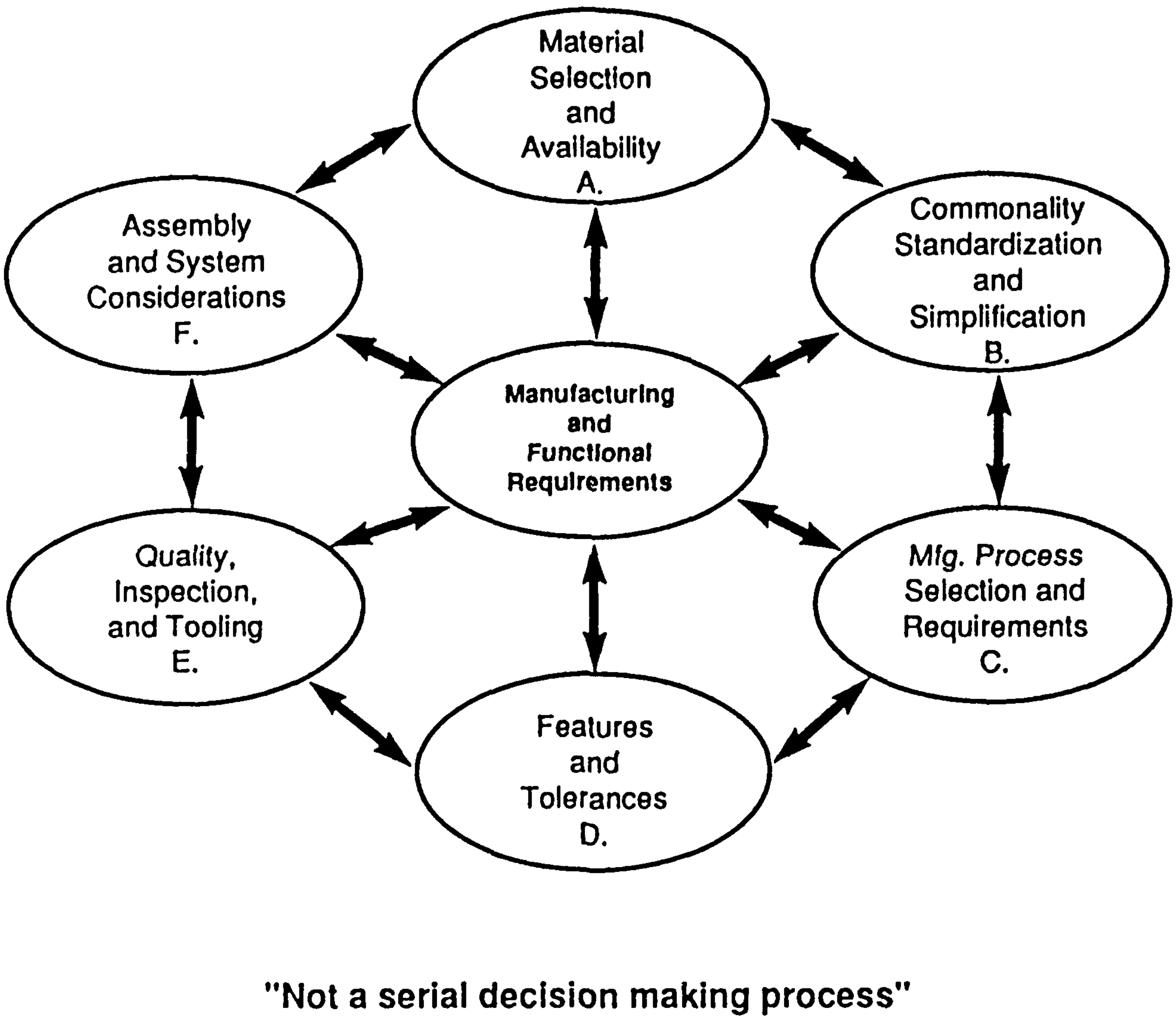

Figure 3.1. Producibility Assessment Network.

Since this is a relative grading system, no attempt is made to derive production costs or the level of technical risk. However, the system can be extended to derive costs and other measurable parameters if a historical database with conversion parameters is incorporated into the evaluation algorithms.

3.2.1 Technical Approach. The evaluation rules used in the proposed system are simple numerical or yes/no type questions which evaluate a particular aspect of design producibility. Some rules generate a simple result based directly on its own inputs, while other rules are inter-related and may have complex interdependencies. Clearly, the weight of each rule can be adjusted to match particular process peculiarities and specific details. The key to this grading scheme is that it is one which tries to encompass all the producibility issues into a single evaluation process. Hence, items which are not normally considered in a technical evaluation, such as material availability, design commonality, or assembly considerations, etc. are also included.

A set of producibility rules can be generated from a variety of sources:

- o Available publications, books, and specifications.
- o Process capabilities studies of manufacturing processes.
- o Interviews with actual producibility, design, and manufacturing experts.

3.2.2 Rating Method. Two ingredients are used to determine the Manufacturability Index (MI) of a metal part: the Weighted Producibility Influencing Factor (WPIF), and the Observed Design Production Difficulty (ODPD).

WPIF represents all the design, material, manufacturing, and environmental factors that have a significant impact on producibility. Since the number of producibility influencing factors is too large, the intention of this project has been to select a list of representative factors to illustrate the methodology. The final version of DPAS however, will be targeted to include 20% of the factors that normally cause the 80% of the producibility problems. Table 1 shows a sample list of those factors. It is important to recognize however, that the list of influencing producibility factors, which is user defined by a producibility team via intensive design and manufacturing surveys, depends on the area of manufacturing technology under consideration. For the Phase I of this research, an empirical study of several metal components defined the producibility factors and established the order given on Table 1. The most influencing factor from a producibility point of view is listed first (tolerances and surface finish) and the least critical is listed last (drawing specifications). Each factor is given a weight relative to its impact on producibility. In a simple way, a factor of great producibility impact is given a weight of 10 and the factor of least impact is given a value of 1.

The ODPD, a relative numerical value, "quantifies" the level of manufacturing difficulty that a manufacturing engineer will have to face during product fabrication. For example, a complex, non-standard product design with non-essential, intricate geometric features would have high production difficulties. Those designs will be rated with high ODPD values. On the other hand, simple standard designs will normally have low ODPD values. The values associated with the observed design production difficulty are determined by the system based on user inputs regarding design specifications and characteristics.

After all the WPIF and ODPD values have been quantified for every producibility assessment factor, an overall Manufacturability Index (MI) can be calculated through the following equation:

$$MI = WPIF(1)*ODPD(1)+WPIF(2)*ODPD(2)+----$$

$$WPIF(n)*ODPD(n). \qquad \text{EQ. 1}$$

Once a final MI value has been calculated, the designer can go back and perform some "what if" queries. By modifying a design feature, the affected attributes are re-evaluated and reflected in a new MI calculation. After a few iterations, the designer can arrive at a preferred design which meet prescribed producibility requirements.

TABLE 1. Producibility Rating Factors.

FACTOR	WEIGHTED PRODUCIBILITY INFLUENCING FACTOR (WPIF)	OBSERVED DESIGN PRODUCTION DIFFICULTY (ODPD)
Tolerances and surface finish	10	ODPD (I)
Production Facilities	9	.
Material Availability	8	.
Machinability	7	Range For
Geometric Features	6	Each Factor
Tooling	5	.
Materials/Mfg. Process Compatibility	4	10 = The Worst
Technical Skills	3	0 = The Best
Assemblability	2	.
Drawing Specifications	1	.

Since this is a "penalty" system, the criteria when comparing two designs is that the design, with a higher MI value, will be the least producible one. It is also expected that those designs, with

an MI exceeding a particular threshold value, will justify its review or redesign as an aid in reducing manufacturing costs. The numerical example provided in section 7.3 shows a sample list of threshold values.

3.2.3 Evaluation Steps. The flexibility of DPAS makes it versatile in that it can be easily used in different scenarios. This flexibility allows the producibility assessment tasks to be performed under individual and independently varying product design development, testing situations, repair and trouble shooting. Variations due to changes and/or differences in vendors, procedures, processes, personnel and experience can all be systematically comprehended within DPAS so that adequate producibility assessments, which are relative, can be made. This versatility is important and fundamental to the utility of the system because no two product design situations are ever alike and furthermore these situations are evolving in time. DPAS' evaluation steps are shown in Figure 3.2.

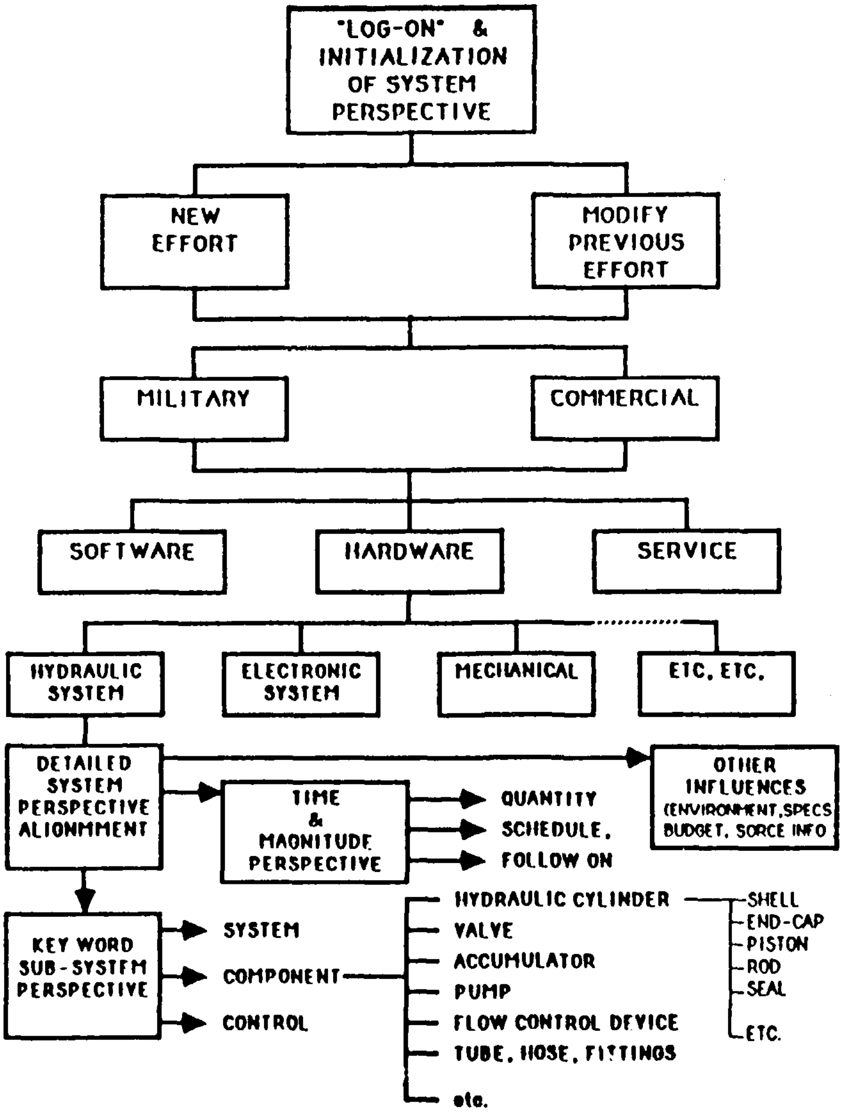

Figure 3.2. <u>DPAS Evaluation Steps</u>.

DPAS' final report includes the global design Manufacturability Index (MI), a list of the assessment factors as shown in Table 1 and their individual Manufacturability Index (MI) value, a list of those questions for which the designer did not give an answer and the associated (system provided) default value, and a detailed list of all the user answers and system calculated production difficulty values.

3.3 <u>System Functional Specifications</u>. The goal of DPAS' project is to develop an advanced engineering software tool easy to learn and with a minimum software training to use it. Most of the information the user needs to know to operate the system will be available on-line so that he/she can fully concentrate on the producibility issues.

It is important to note that rapid changes in the state of hardware and software markets makes any analysis like this one tentative at best. The key issue here is to develop a robust product at minimal cost that can be used in a majority of the installations. Translated into specifics, this means that the product must handle, or be modifiable to handle, all types of exceptions, it must be usable and consistent across platforms via recompilation or network access and must be available to the customer at a palatable price.

This means that DPAS must run on a small general purpose computer (such as generic MS-DOS micro-computers) so that the cost of capital investment is also at minimum. Since different users will have different needs and requirements, DPAS will be designed in such a way that even a very high degree of customization is possible. The knowledge base will be structured so that the users can subscribe to only what they need. The key software issues of the DPAS are listed in the following paragraphs.

3.3.1 Key Features.

- Object oriented language development system. Runtime versions under MS-DOS and UNIX operating system.
- Modular design for both program and data. Incremental update of software is allowed.
- Macintosh-like user interface (including Pulldown/Popup Menu, Window, and mouse) to minimize training requirements.
- Hypertext-like help.
- Integrated text and graphics information.
- Available on both low-end and multi-user computer systems.

3.3.2 Knowledge Representation. The engineering information required by DPAS is characterized by a large number of heavily

interrelated data types and data structures.

From a knowledge representation point of view, DPAS is a hybrid tool. It uses rules and objects to represent knowledge: rules to represent reasoning and objects to describe the domain upon which the reasoning is based. The Rule's universal format is:

IF ... THEN ... DO ...

In other words, every piece of knowledge will be written in this format, where IF is followed by a set of conditions (tests performed on data) and THEN by a set of actions which will only take place if all the conditions following the IF are met.

A collection of rules constitutes a large portion of DPAS' knowledge base. This set of rules is then used by a control mechanism called a Knowledge Processor which dynamically browses through the producibility knowledge base to infer conclusions about product manufacturability.

The performance of the Knowledge Processor may be seen as a problem-structuring task, a notion which applies to such functions as diagnosis, situation assessment, problem solving, decision-making, planning, simulation, training, etc. Similarly, problem-structuring can be viewed as "jumping" from an ill-structured problem to a structured problem by means of an automated analysis tool such as the DPAS. Separate from but strongly related to the reasoning issues, the representation issues are critical in a knowledge-based tool. They represent the manner in which the developer will be able to realistically describe the world of "things" upon which he or she wants to perform the reasoning.

OBJECT = Name..Class(es)..Subobject(s)..Properties

This syntax allows that anything in the producibility assessment process has a name which can be association to a class (category) of object. Each category, at the same time may have sub-categories or sub-objects which can also be described by a set of property values such as size, shape, etc.

The use of a richer description affects the knowledge processing, adding more ways to model a solution to a particular problem. The overall task of knowledge design encompasses both discovering rules (the elementary units of reasoning) and describing the domain they act upon.

3.3.3 Computer Hardware and Operating System. The computer system features, for DPAS development, are shown in Figure 3.3. DPAS will run under a minimum of two main operating systems; MS-DOS and UNIX. (VAX VMS and OS/2 are considered as the next two operating systems for DPAS.)

MS-DOS is a de facto standard for single-task single-user operating systems, MS-DOS computers have the best price/performance ratio with the largest user community. With the release of MS-DOS

4.0 supporting more memory than the well-known limitation of 640K, it is now possible for complicated applications such as DPAS, to run under MS-DOS. Also, in MS-DOS 4.0, more types of hard disks are supported and the 32 MB hard disk partition limitation is lifted. This will allow a bigger database to be stored under DOS without breaking into smaller units. Additionally, DOS under 80386 delivers a computation speed of over 5 MIPS for integer number processing. For a single user environment, this is as fast as a mid-range mini computer such as the VAX 87XX series.

For the low cost multi-user multi-tasking environment, UNIX is the natural choice. UNIX is widely used for high power PCs and MINI computers such as Apple, SUN, APOLLO, Convergent, HP, Pyramid, etc. Earlier development of UNIX was used to develop many well-known operating systems such as Prime PRIMOS and Data General AOS. Some corporations have even developed their own UNIX version to compete with their other operating systems such as AIX from IBM, Ultrix from DEC and Xenix from MS. In short, all major computer companies support UNIX, either as their main operating system or as a secondary operating system.

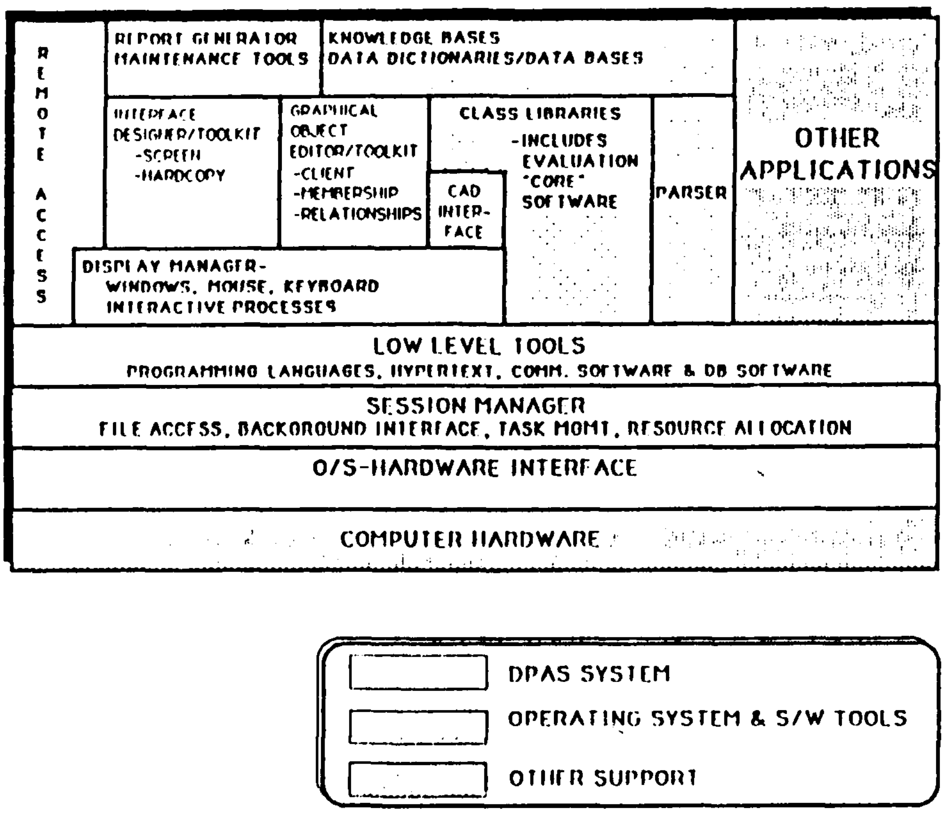

Figure 3.3. <u>The Computer System for DPAS' Development</u>.

3.3.4 **Software Tools.** One important shortcoming of the conventional programming paradigm is that it cannot represent the complex relationship of manufacturing information. Handling this data dependency with conventional programming languages, such as PASCAL, will increase the size of the program and make it difficult to maintain and update.

Due to the quantity and the complexity of the data required by DPAS, the software platform for this project will use an object-oriented programming language, such as Objective-C by the Stepstone Corporation, in combination with a widely used relational database such as DBIII Plus or Ingres with a migration plan to an object-oriented database in the future.

In an object-oriented environment, each piece of data is defined as an object. An object represents an entity and has a number of attributes (or properties) and methods to operate by. Similar objects can share their properties by grouping them together and classifying them under the same class. Classes are further classified as Subclasses and so on to further enhance the complex hierarchical structure of the objects. Objects communicate with others via message sending and message receiving. The action that an object responds to an incoming message is also defined.

In the proposed system, each piece of key information will be modeled as an object with properties such as a set of valid answers, a suggestion value, the last value defined by the user, etc. Both the set of valid answers and the suggestion value are stored information called from the user-defined standards such as MIL-STD or commercial standards. Hence, for a different project or environment, DPAS will be able to use a different set of parameters to evaluate the product accordingly.

3.3.5 **Customizing Capabilities.** DPAS will provide a comprehensive set of user customizing tools which will allow tailoring of the application to match the requirements of a particular industry. The following are three levels of customization capabilities being considered:

- o Operational Customization.
- o Data Customization.
- o Knowledge Processing Customization.

Operational Customization. This type of customization will allow users to tailor the environment in which the applications execute. It will be performed without the need of any user programming. The following features are being considered for the operational customization:

- o DPAS' configuration.
- o Passwords associated with terminals and data items.

- Database capacities.

- Error messages.

- DPAS' subsystems which can be accessed via User Interface Menu.

The User Interface Menu facility provides users with a menu driven, customizable interface for accessing DPAS subsystems and their applications. Each application user can access a set of applications which has been defined by the Session Manager. The Session Manager defines this set of applications through the customization feature in the User Interface Facility.

Data Customization. A customer using Data Customization has, without the need for any programming, expanded tailoring capabilities as follows:

- Items can be added to or deleted from the Knowledge Base and the characteristics of existing designs can be changed.

- Menu and transactions screens can be added, deleted, or resequenced.

- Fields can be added, changed, rearranged, or deleted on existing screens.

- Help screens can be modified.

- Arithmetic relationships between data items can be defined.

- Reports can be customized by rearranging columns, changing column headings, and changing the length of data items.

Operational and Data Customization of DPAS are performed using specially designated user ID's. End users do not have access to customization capabilities. Customization may be done at any time, but it will probably occur regularly as part of a maintenance program and then infrequently for special changes thereafter.

Knowledge Processing Customization. This level of customization provides additional tailoring capabilities for those customers who need specialized processing to satisfy unique business requirements. This level of customization is intended for those companies whose requirements can be met only through extension of the standard processing of DPAS transactions. This advanced customization features include:

- Pre-defined exit points in on-line consultation that can be used for:

  - Extension of data editing logic to match user needs.

  - Data validation against external files and databases.

  - Dynamic interface with other application systems.

- TRACE facility for program debug and test of exit procedures.

4. DPAS' ARCHITECTURE

The major modules of the Design Producibility Assessment System (DPAS) are shown in Figure 4.1. Each module and its submodules are discussed in this chapter. In order to build a workable system on a moderate class of hardware (from super micro computers to mini computers), the system is divided into groups of cooperating knowledge sources, independent algorithmic modules and database management functions. This architecture makes the software easier to maintain, easier to upgrade, and easier to modify in the future.

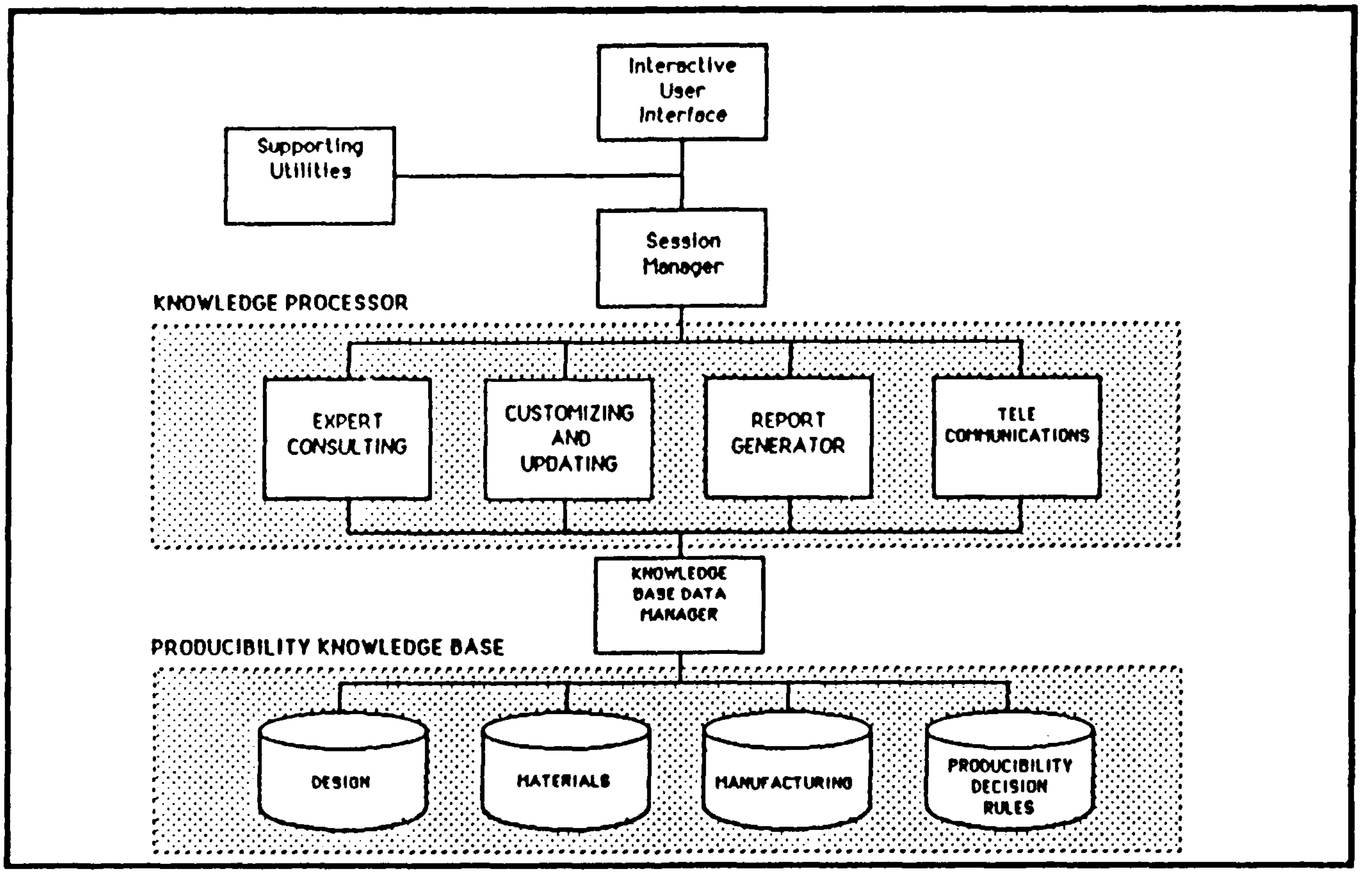

Figure 4.1. DPAS' Architecture.

4.1 Interactive User Interface. There are several different types of user interfaces required for DPAS including interfaces to support:

- o The initial capture of data for new hardware designs.
- o The modification of existing design data.
- o The design, manufacturing and testing knowledge bases maintenance of

- design rules,
- design parameters,
- tooling and fixturing specification,
- manufacturing process plans,
- assembly guidelines,
- etc.

o Maintenance of DPAS knowledge base for

- addition of new rules,
- modification of preferred manufacturing procedures,
- addition of new historic and statistic data.

The following criteria have been developed to guide the user interface development:

o Consistency in design.

- message presentation system.
- screen layout.
- system procedures.
- input and output methods.
- terminology.

o Simplicity and ease of use.

- menu-based system.
- window oriented.
- on-line help.
- on-line users guide/manual.
- Interactive Instruction System (IIS) to guide user through system.

o User control of actions.

- menu selection.
- explanation facilities.
- ability to change responses.

o Usage scenario orientation.

- presentation of requests for data and results modeled after decision making process.
- markers to indicate current location in decision process.

o Message design.

- user centered messages.
- constructive error messages.
- consistent terminology.
- consistent placement on screen.
- limit or prevent user from making mistakes.

Actually, a key part of the user interface of DPAS is the documentation which accompanies the product. The design for the documentation is a critical part of the overall system design. The following criteria have been developed as the design goals for DPAS user documentation:

- o Modular approach for different user types.
  - DPAS Installer.
  - end user.
  - database administrator.
  - knowledge base administrator.
- o Task orientation.
- o Quick reference aids.
  - table of contents
  - index
  - bolded glossary references
  - cross-references between manuals, training aids, and on-line help.

The major tasks for the user interface module are displayed in Figure 4.2. As basic components of any software, the two major classes of information between users and the system are input from users to the system and output from the system to users. Input can be classified further into input data and commands. Output can be prompts for more data, prompts for the next level of commands, messages, or information display. To accomplish these functions, the proposed DPAS' user interface module will consist of several submodules as shown in Figure 4.3. To simplify the user interface, all commands and options will be handled by combinations of multiple windows and menus.

The menu system provides three types of menus:

- o The persistent pull down menu provides a display across the top of the user screen with system commands organized in major categories which may be accessed by selection of the category which displays the contents of that category and then selection of the appropriate command.
- o The pop-up menu capability provides information or requests input in a temporary mode which immediately disappears on data entry.
- o The persistent menus display information which stays displayed until the user de-selects that menu. The window system is responsible for the management of the various types of windows being used at any point in time by DPAS. This management includes direction of I/O and maintenance of the display stack which determines which windows are currently exposed.

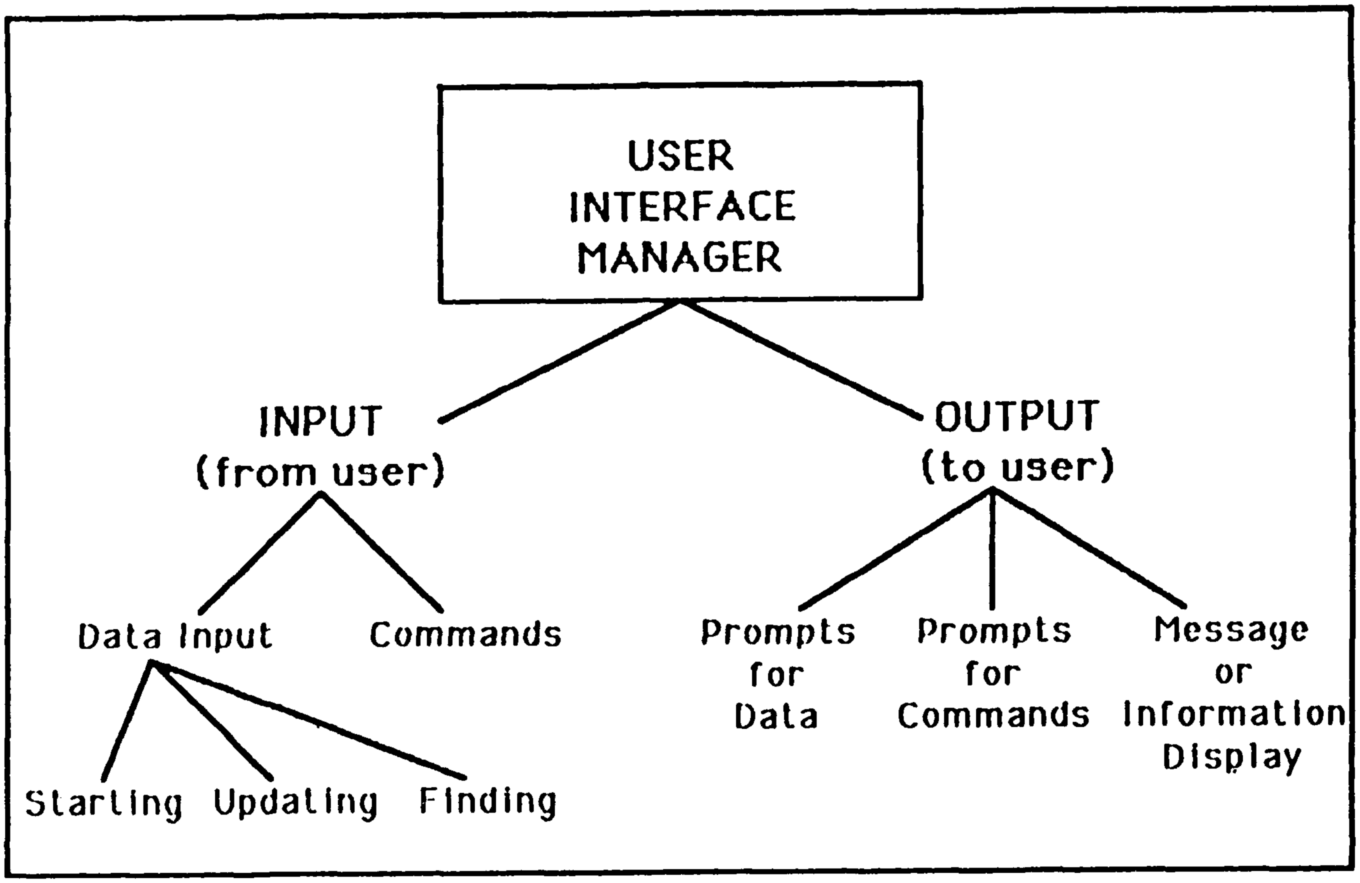

Figure 4.2. DPAS' User Interface Tasks.

The command parser is responsible for the parsing of simple DPAS commands. It provides the necessary interface for the experienced regular user. For less experienced users who may not remember specific access commands, DPAS includes a query processor. The query processor provides the capability for the entry of queries to any of DPAS databases or knowledge bases in restricted natural language format. Depending upon the mode of access, once the information is located, pop-up menus, graphics or forms may be invoked by the utilities responsible for execution of that mode of access. For example, the plan editor would be automatically invoked for the retrieval of previously generated design.

The editor window component in the user interface provides a "hypertext" interface to the editor utility. This capability allows the user to see at a glance which of the producibility factors are constrained to their position in a set of constraints. The benefit of this approach is that the design can be first evaluated by the system and then customized or updated as needed.

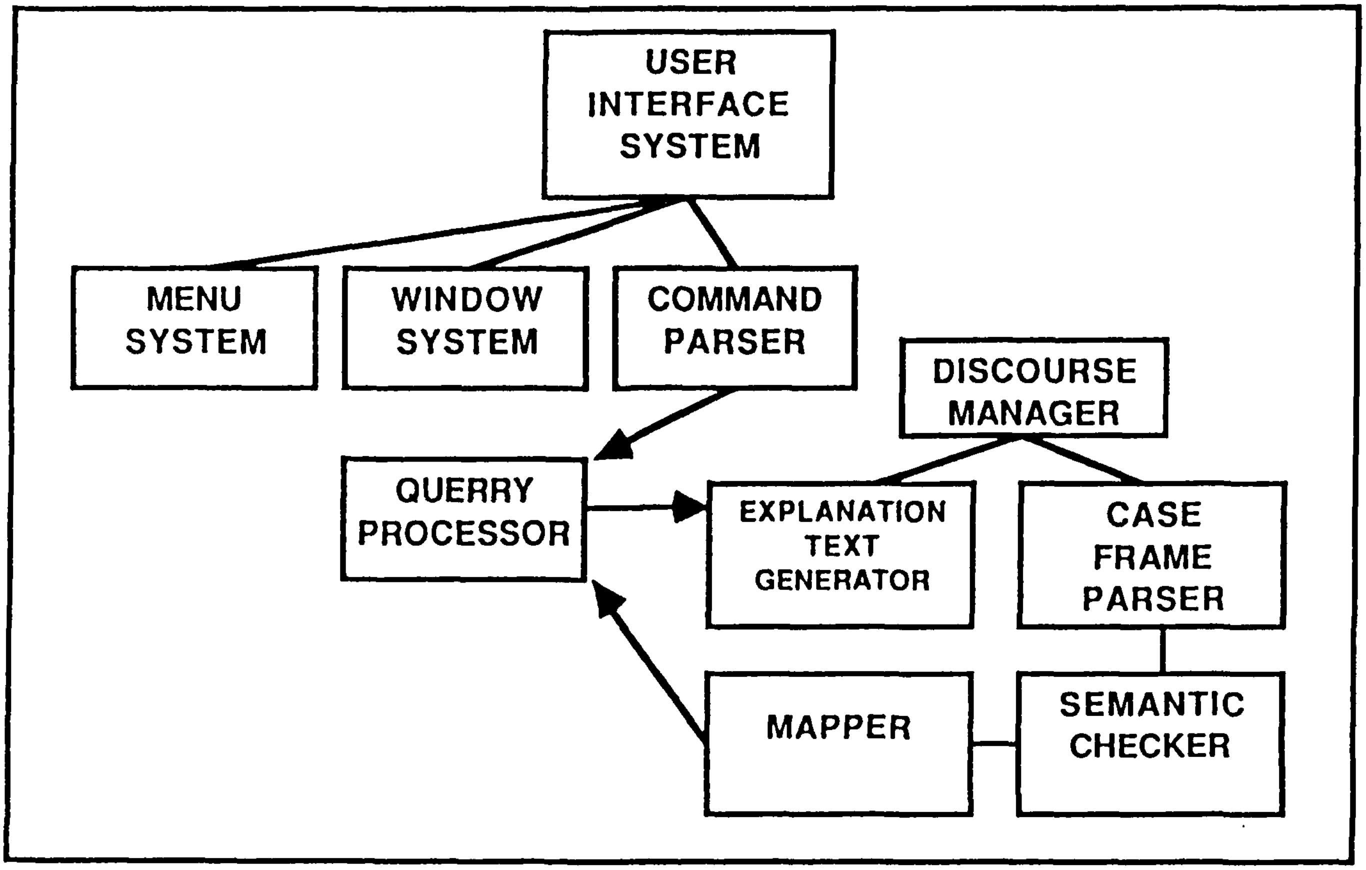

Figure 4.3. DPAS' Interface Component Structure.

4.2 Supporting Utilities. Figure 4.4 illustrates the set of utility modules which will be provided in DPAS. The following sections describe each of these facilities and their functionality.

The database maintenance utilities fall into three basic categories. The first set of utilities are the least complex. They embody a set of form and menu driven applications for maintaining the data in the databases identified in Figure 4.1. These utilities would be designed for the end user. They would also provide the capability to access the data for use outside of DPAS. The second class of utilities are targeted for support of the local database administrator. These utilities provide support for database generation, data dictionary management, data compression, data security control, report generator, and database consistency analysis. The third set of utilities support the maintenance of the data integration information. This includes updates to the conceptual data model, external and internal schemas and their conversions.

4.2.1 Knowledge Base Construction Utilities. The knowledge base construction utilities represent one of the most complex components in DPAS. They provide the following functions for a particular knowledge source:

- Knowledge base summarization. Explains to the user what the scope and extent of the current knowledge in that part of the system entails.

- Knowledge acquisition. Provides a menu and template interface for the acquisition of schema and rule structures from the user.

- Knowledge consistency analysis. Checks that the rules entered do not contain conflicting information. In general this cannot be guaranteed but some simple checks can be performed to catch gross errors.

- Knowledge completeness. Several of the knowledge sources are structured selection sources, for these knowledge bases a tree walk algorithm can be constructed to check the completeness of coverage of the rule sets provided and generate the missing condition combinations.

- Knowledge source try out. Provides test generation utilities to simulate the operation of a single knowledge source without the need for complete definition of the entire system.

- Test case execution. Provides a utility for off-line testing of a set of test cases to insure that use of these utilities to maintain a knowledge base do not introduce errors which would produce invalid results on a known set of bench mark examples.

4.2.2 Knowledge Base Maintenance Utilities. The knowledge base maintenance utilities include the construction utilities used in the mode of adding additional knowledge to the individual part design in DPAS. Added to these capabilities are the utilities for constructing and managing knowledge base versions, user views, and explicit management of histories. Through the use of these utilities, the system manager can experiment with the addition of new rules. When he is satisfied that the new structures are working properly, he can establish the development system as the default system. This capability allows multiple experts to evolve DPAS' knowledge bases, recommend updates to the system manager, and still maintain the control necessary to get his job done.

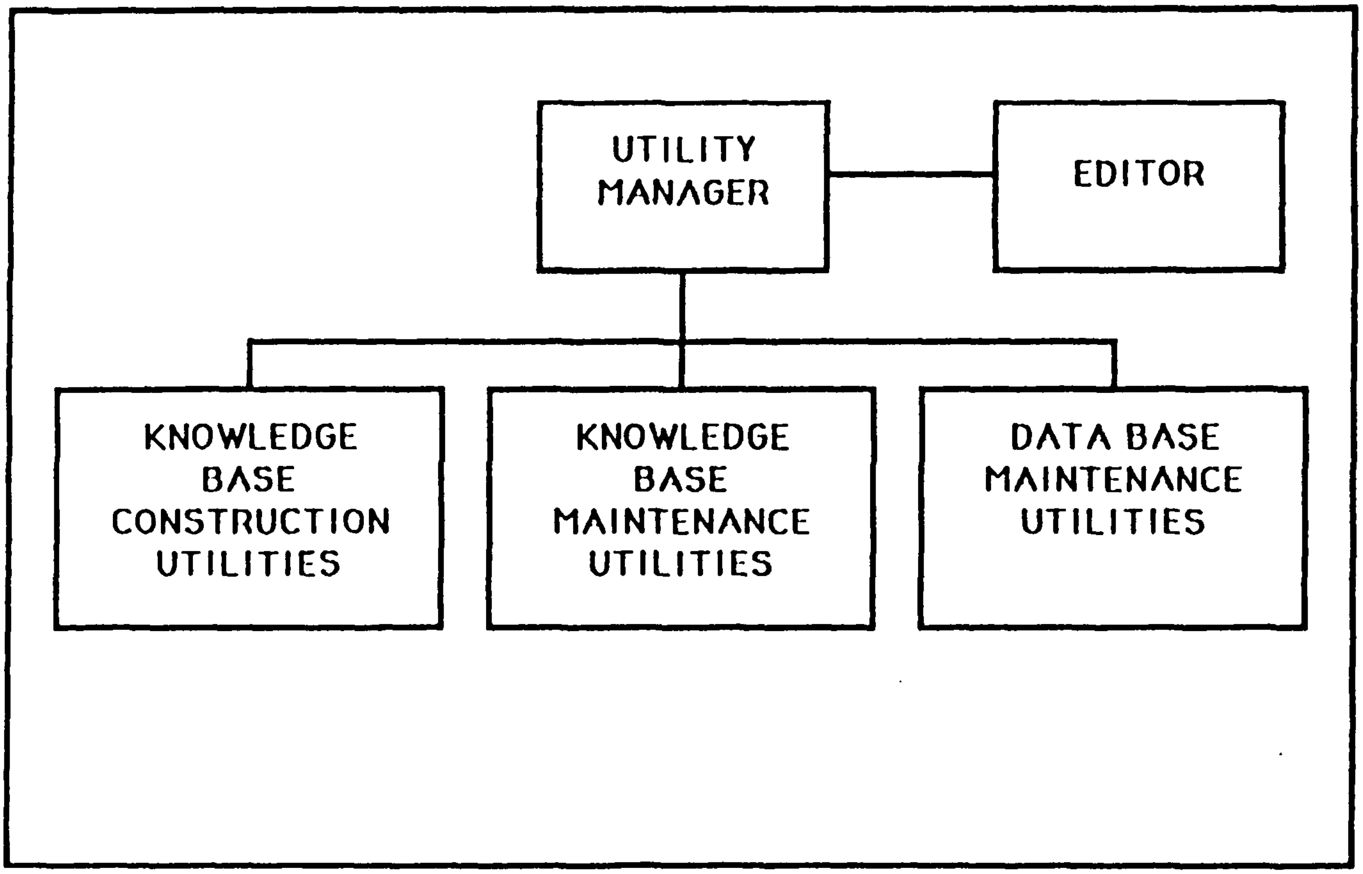

Figure 4.4. DPAS' Development and Support Utilities.

4.2.3 Editor. One of the major shortfalls of existing deterministic based producibility planning systems (both knowledge-based and traditional), is that the reasoning process history is lost once the plan is constructed. Not only are the systems incapable of explaining why a plan turned out the way it did, but more importantly they do not provide the user with the capability to interactively tune the plan. The knowledge based editor concept in DPAS is unique. It provides the full power of the knowledge sources and the history of the current producibility profile on a part during an editing session. In fact, the entire producibility analysis process can be performed interactively through the plan editor by editing an empty sketch file. This allows the designer to interact with the decision-maker concept of DPAS. The user can paint the design concepts, while DPAS fills in the details and checks for constraint violations.

The designer can call up a design to make modifications based on problems experienced in the shop, the availability of new equipment or tools, or because he has thought of a new design approach (for example, a new fixturing concept). The conceptual design is presented in "hyper-text" in a plan editor window as previously described in the section on the user interface. Within

this window, each of the design/producibility attributes are all mouse sensitive. The designer can select any item for editing. In the cases of processes and operations he can select groups of items. He can query the system for the rationale associated with the existence of a particular item. He can propose changes to the item (for example, use of alternate components) and the editor will call up the appropriate knowledge sources to evaluate the impact of the design change.

4.3 Session Manager. The session manager monitors the overall activity in DPAS, interfaces with all other modules, and allocates the appropriate resources when required. From the initiation of a user session, a number of complex resources must be organized and controlled without the direct involvement of the user. This is the primary task of the session manager. Because of the complexity of the interactions which a user might have with DPAS, it was determined that the session manager itself will have a rule based component at its core. The rule based component keeps, in its working fact base trace elements which record the usage history of a session. Thus, if the user decides to "back-up" and change previous data on selected menus or prompts the rules, the session manager will be able to determine which "inferences" of the system must be undone, which facts retracted and also which prompts and other menus must be redisplayed. In this sense the session manager provides a "visi" like flavor to DPAS' user. That is, it provides the mechanisms for propagation of changes throughout the system.

The basic functions of the session manager include:

- Resource management
- Command processing
- Data flow control
- Session initiation
- Session termination
- Session control

The major components of the session manager are shown in Figure 4.5. At the core of this module is a session management knowledge source which has already been discussed in this section. The session history keeps track of at least one previous session of all users. After the sign-on procedure, a user has options of either creating a new working session with a unique name or resuming the previous session at the point he or she signed off the system.

The DPAS' data manager, working under the session manager, handles data flow in and out of the knowledge source as needed. Two main types of data are the previous user profile knowledge base which contains results of previous producibility assessment

sessions, and the static knowledge base which contains information describing standard design and manufacturing criteria.

The display manager is responsible for the screen displays for all the supported display devices. Since the system is targeted for more than one kind of computer and operating system, the display manager will have to recognize more than one display device and generate compatible screens for all of them.

The resource allocator submodule provides the operating system feature of the session manager. It prioritizes and assigns system resources to tasks competing for the same resource and the task manager controls the execution of tasks. A few important functions of the task manager are scheduling tasks, assigning priorities to tasks, breaking ties for tasks, detecting global error and system recovery.

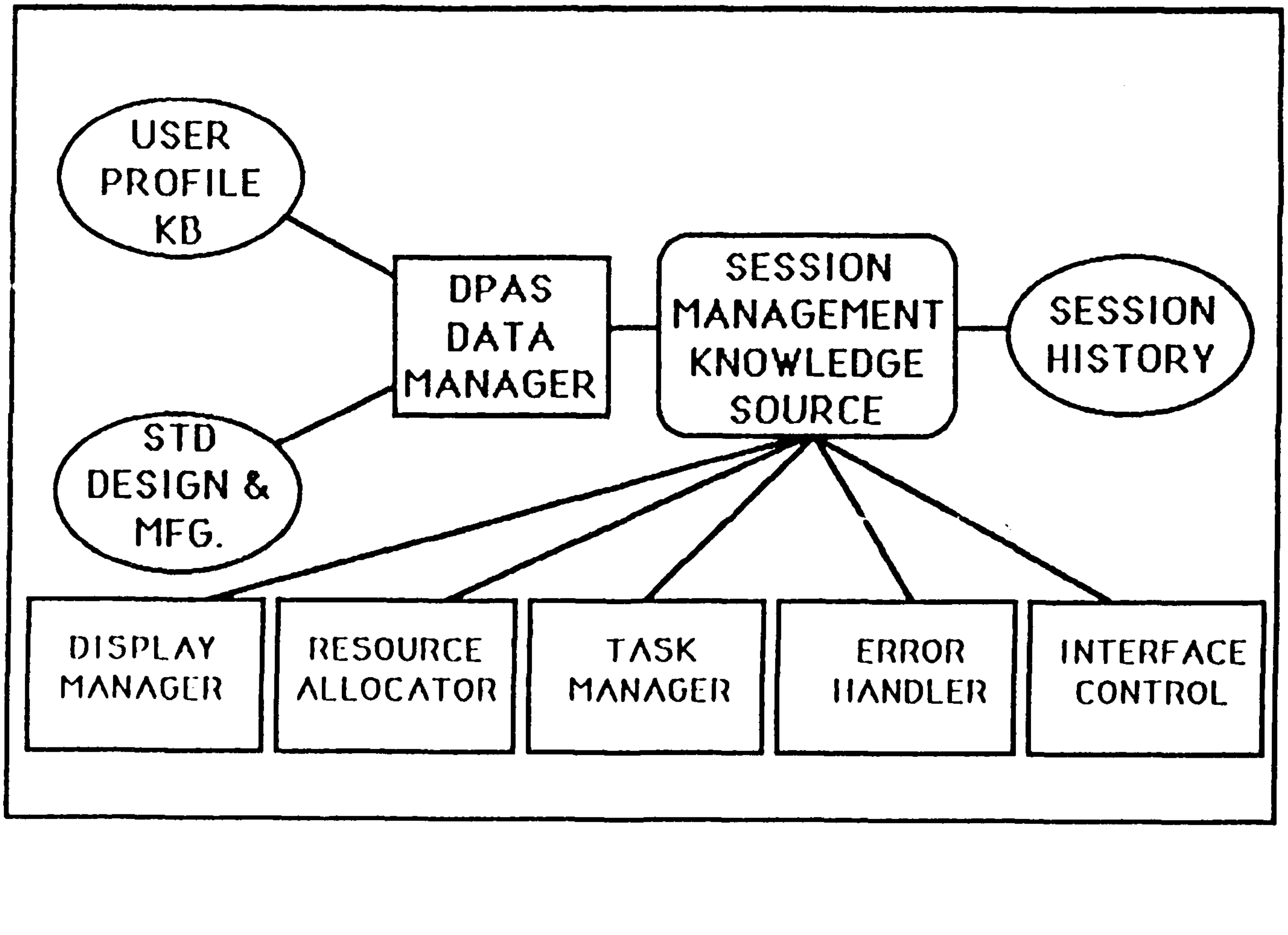

Figure 4.5. Session Manager Anatomy.

The session manager controls interfaces to all of the other major modules in DPAS. Key interfaces are those to the command parser of the user interface and the Common Data Model (CDM) processor of the data interface utilities component.

4.4 **Knowledge Processor Module.** The knowledge processor module is DPAS' toolbox, through which the user accesses all the system working capabilities and the various system resources. With it, the user can perform producibility evaluation tasks or customize and update the producibility knowledge base according to special industrial requirements. The user can also produce several different types of reports, access the system from a distant location, or require special statistical information to reflect design evolution or improvements.

The functions necessary to encompass the complete spectrum of DPAS' planned capabilities are shown in Figure 4.6. Each of these functions can be accessed via the DPAS' executive menu.

4.4.1 Expert Consulting. The expert consulting portion of DPAS contains software that uses information from both the producibility knowledge base and the participating user in order to arrive at a conclusion. With it, the user selects the goal of a working session which will direct the knowledge base data manager in accessing the appropriate consulting database.

By executing this function, the user will have the opportunity to set the working stage for the system declaring the assessment standards to be used, design, manufacturing, testing, etc., and the type of standard specifications to be used, etc. In every consulting session, the user has control of it through responses to prompt DPAS' request for information.

The expert consultation function is also a crucial part of the development of DPAS' knowledge base. Running a consultation while developing the knowledge base allows the checking of the development progress periodically, decreasing the possibilities of future software design changes and reprogramming.

One important feature of the expert consulting function is its on-line help capability. With it, DPAS uses a user explanatory information about prompts. For the purpose of the demo program, the F1 key invokes DPAS' help feature. When a prompt appears, the user can press the F1 key for a help message. If this particular help feature has a value, a message appears to further explain the prompt and provides additional explanatory information regarding the question at hand.

4.4.2 Customizing and Updating. The customizing function provides a comprehensive set of user customizing features which allows tailoring DPAS to match the requirements of a particular

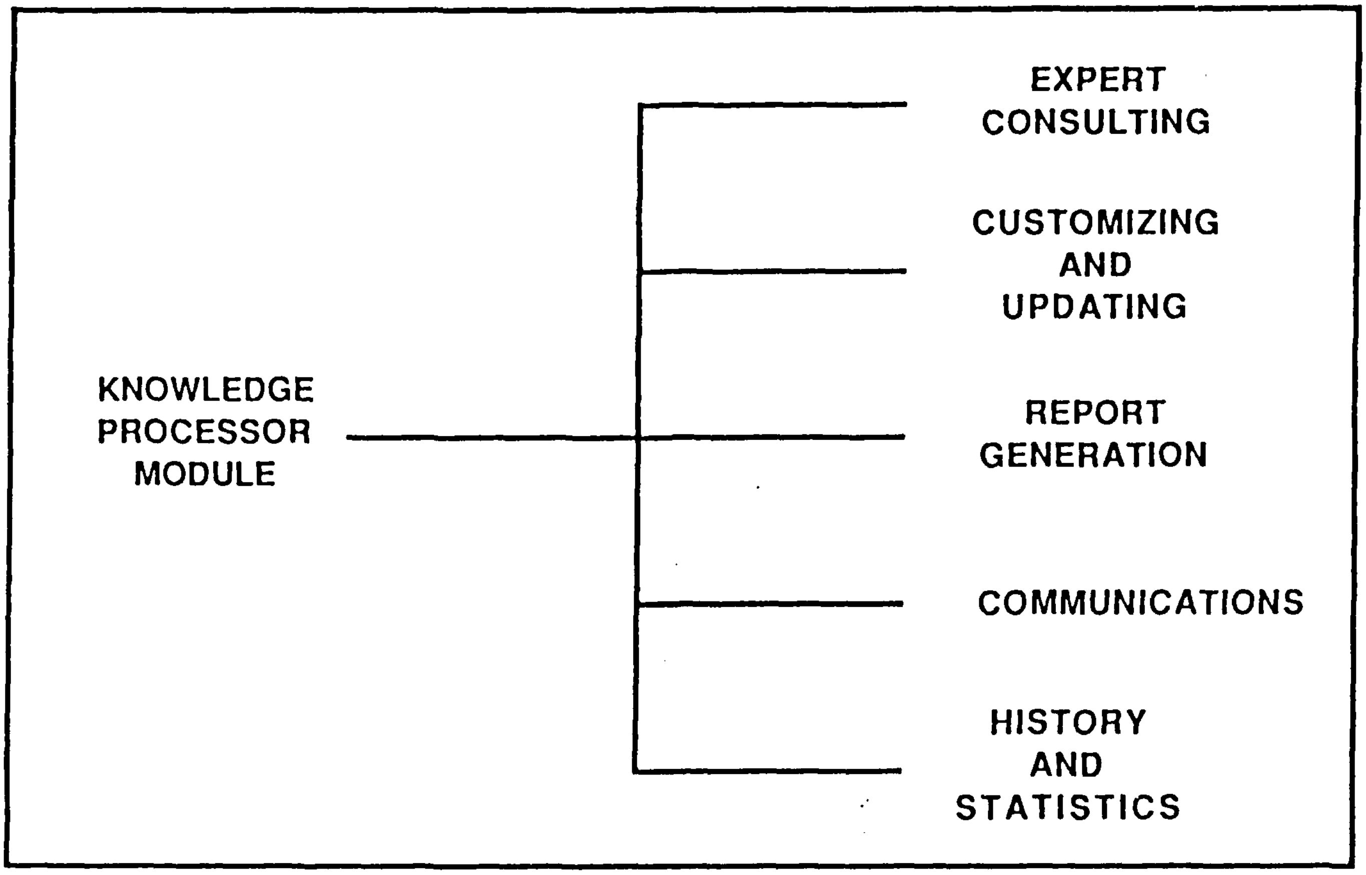

Figure 4.6. Knowledge Processor Functions.

fabrication environment. Three levels of customization capabilities can be considered:

- The operational customization which allows the user to tailor the environment in which the application executes. This customization involves DPAS' capabilities to define different system configurations, pass word generation, job schedule, etc.

- The data customization. It allows customers add to or delete data items from the knowledge base or change the characteristics of an existing item. Menu and transaction screens can also be added, deleted, or resequenced. Reports can be customized by rearranging columns, changing column headings, and changing the length of data items.

- The third type of DPAS' customization is for those users who need specialized processing to satisfy their unique

business environment, such as extensions to data editing, special data validation, advanced customized reports and so on.

The updating function controls the authorized modifications to the knowledge base. This function is particularly important because it helps to adapt the working data to those approved by commercial or industry standards. Similarly, it helps to assure that the knowledge base contains only accurate data. Inconsistency between two entries, representing the same "fact," is an example of lack of integrity that sometimes results from data redundancy.

4.4.3 Report Generator. The report generating function of the knowledge processor module is responsible for the production of detailed evaluation reports. They can include a list of all the evaluating categories. Reports can be produced on request and displayed on the screen or spooled to a hardcopy printer. Each report can be selected so that data subsets, such as a separated evaluation category, can be analyzed independently. The output reports produced by DPAS can be highly customized to fit each user's application. Typical detailed and summary evaluation can be produced by evaluation category or vendor identification.

4.4.4 Data Communication. The communication function of the knowledge processor module makes it easy for a user to communicate with DPAS from a remote computer workstation. This function specifies the way in which a "consulting" computer and a remote installed DPAS program communicates with each other. The communication function includes such things as the telephone number, protocol parameters, macros, and log-on sequence used to reach the DPAS from a distance computer.

Before the user originates an answer or a call, the module displays a communication directory. It lists the name and data of the remote system the user can call. It coordinates the activities and selects compatible parameter settings. The system can also provide the means of answering a call from another computer and the transferring of files error-free. To communicate, the user must know what operating system the other computer is using, what character formats it will accept, and other characteristics, such as data transmission mode and speed.

4.5 Knowledge Base Data Manager. The knowledge base manager module serves as a translator/interface between the knowledge processor module and major databases. It addresses the function of knowledge manager in DPAS. We consider knowledge management to be the control of the interaction between one "agent," the user, and other "agent," the system. As indicated in Figure 2, there are several traditional databases which are required to support the producibility assessment system. Since in any particular company some of these databases will already exist (possibly on other computers) the system must provide a mechanism for integrating with or at least interfacing with these external databases.

The management of a knowledge base is in essence a high-level

cognitive task. For such a task, the module must be provided with equally high-level tools; that is, tools which allow the user to focus attention on the task at hand, rather than on the user of the tools. With this idea in mind, this module will be designed with power and transparency to the user.

4.6 Producibility Knowledge Base. This module contains the core of the producibility assessment logic in DPAS which calls upon the knowledge sources illustrated in Figure 4.1. The producibility decision rules stored in this module are the rules that will ultimately be combined to help form the producibility assessment rules of DPAS' knowledge base. They represent isolated observations, and although categorized, do not accurately represent the total number of categories, or the total number of rules within a given category. Every manufacturing industry, fabrication shop, engineering design or manufacturing expert has his own unique set of rules to operate by. Some of these unique rules may be inaccurate or even incorrect for other applications. Hence, the realization is that rule collection, review, organization and definition is a significant effort which must be explicitly understood, integrated one to the other, tested and proven to develop a fully functional system.

The knowledge domain for producibility is significantly complex and can be influenced by a number of manufacturing strategies and functional factors. The selected approach in this project is to assume that the strategic factors are given and not to attempt to simulate any of the human reasoning or logic involved in the organization or strategic "drivers" for producibility. The direction is to initiate the producibility assessment process after the creation or definition of a conceptual design with the associated functional requirements.

Within this framework, the producibility knowledge base contains the knowledge structures, such as facts and design rules needed to support hardware design producibility evaluation. This knowledge base will include concepts, relationships between concepts, rules for manipulating these data structures and meta-rules. A variety of representational schemas, including frames and semantic networks, have been explored in hardware design discussions.

Included in the knowledge base are the engineering data and standards. This database contains information on design standardization and simplification criteria that result in producible products. It also contains manufacturing process information, tolerance specifications and hardware design considerations.

5. DEVELOPMENT PLATFORM

Two of the key issues in software development are platform related. What hardware/software platform will be used to develop the system? Similarly, what platform will the developed system ultimately run on? The answers to these two questions are critical and need not be the same. The reasons for their importance follow:

Various considerations entering the platform decision include cost, compatibility with current software, software tool availability and hardware capabilities. Unfortunately, many times the implications of these considerations are not fully thought out. For example, which is more costly, 6 months of development time by a programmer analyst trying to implement a good user interface or a $5000 piece of software that allows him to do the same thing in 2 months? OR, how much compatibility is really necessary? How many different programs need to run on the same system? How many need only to share files? How many need not communicate at all? OR, how many software tools do you actually need? What are they? Most computers get used for word processing, spreadsheet, database, and CAD related applications - and those applications are available to some degree on any system. The flip side is that quality software development tools are not necessarily available on every machine. NextStep is an order of magnitude more powerful than the features found in Suntools, which are in turn light-years ahead of what is available in PCs.

In addition to considering such questions about a particular platform, questions must be raised regarding the need/desire to use the same platform for both development and delivery. While the development environment has need for more sophisticated software development tools, the delivery environment does not. If the development tools can generate portable code, it may only be necessary to recompile for the target machine. Even in cases where 100% source code compatibility is not achieved, the cost of recoding a percentage may be far beneath the additional cost incurred by limiting development to the delivery platform if it is much weaker.

The point behind these questions is the following: What do you really want to pay for - guts or frills? Easy to use interfaces aren't always easy to program and thus can soak up an abnormally large share of development effort. The use of state-of-the-art development tools minimizes this burden so that the project effort can be focused on solving the real problem.

Development of DPAS requires a considerable amount of exploratory development and software engineering activities to establish an affordable delivery environment. During this phase, we focused the prototyping effort on the use of microcomputer-based tools as our intended delivery vehicle. For the production system, however, we will focus our efforts on the use of a production knowledge engineering environment. The following sections describe the development and delivery environments used in Phase I and Phase II efforts.

5.1 <u>Development Architecture (Phase I)</u>. Phase I effort to create a demonstration model for DPAS used an IBM PC/AT with the following system configuration:

- MS-DOS 3.2
- 40 Megabyte hard disk
- 640K RAM memory
- 1 EGA Card
- 1 EGA Color monitor

Microsoft C5.0 was used as the compiler for the demonstration system, in combination with the C Worthy tool kit as the development tool.

5.2 <u>Development Architecture (Phase II)</u>. The Development activity for Phase II is expected to be accomplished using an object oriented programming language on an 80386-based PC or a 68030-based workstation. Similarly, we see a need to ultimately provide versions which run on the IBM PS/2 and Digital Equipment's MicroVAX. This class of machines provide the necessary combination of database, graphics, and knowledge-base manipulation. An advantage of the DEC and Sun environments over MS-DOS is the availability of a better window-based operating system and a wide selection of software tools including the object-oriented programming support such as Objective-C and VBase.

For the MS-DOS machine, DPAS will use MS-Window 386 as its main development tool for the user interface. On the UNIX-based workstation, X-windows will be utilized for information presentation.

6. FUTURE DEVELOPMENTS

The last several years have seen the blossoming of computer-aided techniques in design engineering, especially in circuit design (Electrical Design Automation, EDA), mechanical design (Mechanical Design Automation, MDA), software design (Computer Assisted Software Engineering, CASE). Unfortunately, all of these advances have focused on improving the productivity and quality of the design process itself, with little coupling to the domains of the product design and product manufacturing.

The Design for Producibility Assessment System (DPAS) envisioned through the development of this project is possible with available computer technology. The necessary knowledge can be captured from experienced design and manufacturing engineers and from presently available bibliographic resources. It is visualized that DPAS will go beyond current producibility assessment systems. In addition to the producibility rules that provide a Manufacturability Index (MI), DPAS could also include direct design interpretation from a CAD workstation. With it, a designer can, after initial creation of a hardware design, evaluate the manufacturability of the design and rapidly change physical manufacturing information on-line, as often as required with immediate visual feedback. Following this approach, design engineers will be capable of delivering hardware prototypes which have already been evaluated as manufacturable. A schematic overview of a CAD/DPAS integration is depicted in Figure 6.1. It is the intention of CIM Systems to explore, in more detail, this promising opportunity as part of a Phase II effort.

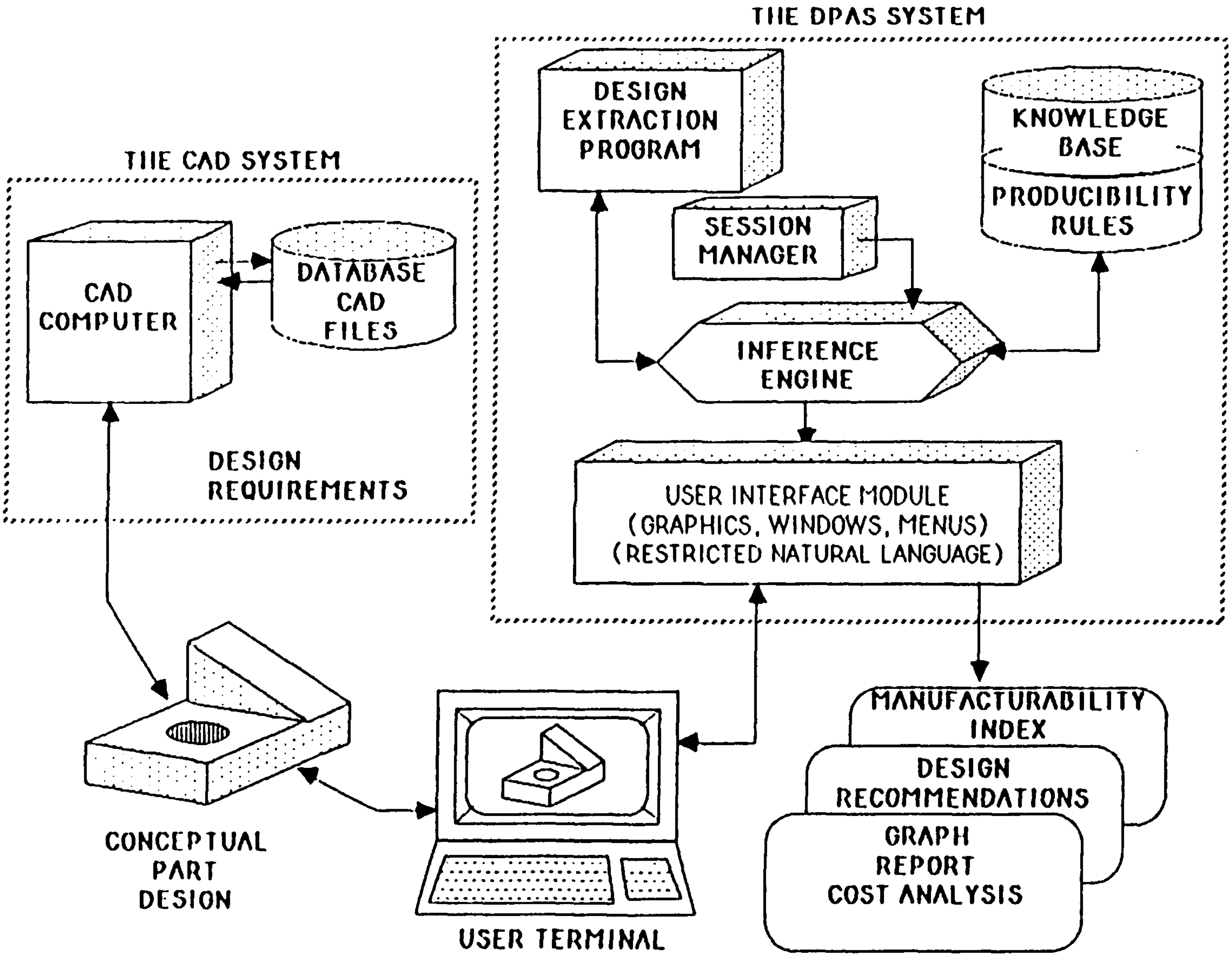

Figure 6.1. Schematic Overview of CAD/DPAS Integration.

7. DPAS DEMONSTRATION PROTOTYPE

7.1 <u>Prototype Intention</u>. The demonstration system constructed under this contract illustrates the following features and capabilities:

- o Identification of some producibility assessment factors and their interrelationships and impact on hardware design.
- o Organization of the many different kinds of information in the databases supportive to DPAS.
- o Calculating and tracking the producibility index based on analysis of design attributes and the user responses.
- o User assistance with generation of producible hardware design.

The demonstration prototype uses a MicroSoft C compiler and the C Worthy tool kit as its development tools. The prototype system runs on a standard IBM-AT computer.

7.2 <u>Prototype Architecture</u>. The research team developed a demonstration prototype using the hardware and software platform described above. The prototype architecture, includes a materials database, a design library, a manufacturing processes database, and a producibility assessment knowledge base.

7.2.1 Materials Database. The materials database includes basic information of thirteen materials stored as part of the DPAS knowledge. This information includes data on the different standard forms available for these materials, number of suppliers, strategic condition and their machinability. The material machinability information is based on the use of the B1112 steel as a reference metal 100% machinable. Therefore, a metal with a 150% machining rate would be 50% more machinable than the B1112 steel. Similarly, a rating of 75% would be interpreted as being 25% less machinable than the B1112 steel.

TABLE 2. Materials Database.

MATERIAL	STD. AVAILABLE FORMS					NO. OF SUPPLIERS	MACHINABILITY
	STRIP	SHEET	BAR	WIRE	TUBE		
B1112: Cold-Rolled Steel			X			3	100
C1117: Cold Finished Steel (Unleaded)					X	2	90
C1117L: Cold-finished Steel (Leaded)					X	2	142
C1018: Cold finished and hot-rolled steel					X	2	75
C1141: Hot-rooled steel (*)			X			3	70
C1040: Cold-finished and hot-rolled bars	X	X	X	X	X	4	64
C1045: Cold-finished, hot-rolled bars and forgings	X		X			1	55
4140 Steel: Chrome-Molybdenum	X	X	X	X	X	4	57
4340 Steel: Chrome-Nickel-Molybdenum	X	X	X	X	X	4	52
4620 Steel: Nickel-Molybdenum	X	X	X	X	X	3	58
6150 Steel: Chrome-Vanadium	X	X	X	X	X	3	50
303 Corrosion-resisting 3 free-machining steel (*)			X			2	65
17-4PH Precipitation-handling, corrosion-resist steel	X	X	X	X	X	4	60

(*) For illustration purposes, these materials are considered strategic

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7.2.2 Design Library. The design library includes a listing of geometric features that allow the DPAS demonstration prototype to evaluate their production difficulty. In the producibility evaluation of a component, every design is considered as a set of well recognized geometric features with special meaning for design and manufacturing engineers. The list of geometric features included in the demonstration is shown in Table 3. A drawing of each feature is included in Appendix B.

TABLE 3. Feature Library Listing

SLOTS		
* Thru slots	- Simple slots	- Open slots
		- Closed slots
	- Complex slots	- Open stepped slots
		- Closed stepped slots
* Blind slots	- Blind simple slots	- Open slots
		- Closed slots
	- Blind complex slots	- Open slots
		- Closed slots
* Plunge slots	- Plunge simple slots	- Open slots
		- Closed slots
	- Plunge complex slots	- Open slots
		- Closed slots
HOLES		
* Simple holes	- Thru holes	
	- Blind holes	
	- Stepped holes (counter base)	
* Complex holes	- Blind stepped holes	
	- Internal groove holes	
	- Internal broached holes	
	- Reverse operation holes	
	- Threaded holes	
SURFACES	- Simple surface primary	
	- Simple surface secondary	
	- Complex surface primary	
	- Complex surface secondary	
SHAFTS	- Simple shaft	
	- Complex shaft	
	- Subsequent shaft features	
	- External Features	- Chamfer
		- Radius
		- Groove
		- Key way
		- Thread
		- Knurl
	- Internal Features	- Chamfer
		- Radius
		- Groove
		- Thread
	- Drilled Holes	- On center
		- Off center

7.2.3 **Manufacturing Database.** The manufacturing database includes information concerning the production capabilities of twelve primary manufacturing processes and the production capabilities of several turning, milling and drilling machines. This information is shown in Tables 4, 5, 6, and 7. The following is an explanation of the information included in these Tables.

Raw Material Form.

Most processes have characteristics which require that the input material be of a given form. This column in the tables indicates the range of input material forms for each process.

Size.

Size refers to the physical measurement of the workpiece, by weight, or by dimension.

Maximum.

The maximum size refers to the largest size normally produced by the given process. It does not include exceptions or specials which could be produced.

Minimum.

The minimum size, on the other hand, refers to the smallest size normally produced by the given process.

Production Rate.

The rate of production is stated in terms of units per period of time. This is expressed as a range since there are a number of factors which can influence the rate.

Material.

Some materials are found to be more adaptable to a process because of their inherent characteristics such as cutting index. It is the broad families that are listed in the column under material rather than the singular types within any one family.

Tolerance.

The column refers to the process tolerance. It is intended to show range rather than exactness.

Surface Finish.

The column refers to the surface finish normally associated with this process. It is a measure of surface irregularities expressed in micro-inches.

Optimum Lot Size.

Each process has an economical or preferred production rate range. It is within this range that the total cost per unit is minimized.

TABLE 4. Primary Manufacturing Processes Capabilities

APPLICABLE PROCESS	RAW MAT'L FORM	SIZE MAXIMUM	SIZE MINIMUM	PRODUCTION RATE	MATERIAL CHOICE	TOLERANCE INCH	SURFACE ROUGHNESS micro inch	OPTIMUM LOT SIZE
1. Extrusion	Billet	8"-10" dia usually	.050" Sections Possible	2-300 parts/minute	Any ductile material	± .005" ± .020" Common	125-63 Depends on Die and Material Used	>10000
2. Impact Extrusion	Bar - Rod Preforms	4" dia x 12" lg	Fraction of oz Walls as thin as .003"	30 pts/min and more for small parts	Any ductile material	± .0005" or closer Common	63 - 125	>10000
3. Die Rolling (*)	Bar Rod	75" lg x 330 lbs possible 23 sqin cross section	1 1/2" lg	20 - 60 parts/minute	Any forgable material	Broad tolerance range	125	>10000
4. Die Forging (*)	Rod Bar	550 dia 1000 sq in. area	1 Ounce 3-25 dia. Common	40 parts/minute	Any forgable material	± .015" Possible	125 Average	>10000
5. Sand Casting	Molten Ingot	Limited usually by pouring ladle capacity	Fraction of pound	1 - 140 cycles/shift	Any pourable material	±1/32"-1/16" on small parts ±1/16"-1/8" on medium-large	90 - 190	<100
6. Die Casting	Molten Ingot	30 lbs has been made 10 dia average	.001 lbs.	200-400 parts/hour	Zinc, Aluminum, Magnesium, Brass	± .003" to ± .010"	125 or Better	>10000
7. Centrifugal Casting	Molten Ingot	1000 dia 55" OD 347" long	2" I.D. and 1/4" Wall	1 - 7 parts/hour	Any pourable material	± .000" on I.D. ± .020" on O.D. ± 1/32" to 1/8" Generally	125 Obtainable 250 Average	>1000
8. Permanent Mold Casting	Molten Ingot	300 dia 600 dia Alum have been made	Fraction of pound	50 - 400 parts/shift	Will handle all molten metals; non-ferrous best	± .005" Obtainable ± .015" Average	125 - 250	>10000
9. Shell Mold Casting	Molten Ingot	200 dia 25 dia Average	1 Ounce	12 - 60 parts/hour	Any pourable material	± .005"	63 - 250	>1000
10. Investment Casting	Molten Ingot	100 dia max Obtained 24"x8", 60 dia Usual max Usually under 10 dia.	Few Ounces	100/hour	Any pourable material	± .002"-± .004" Obtainable ± .003" Common	125 and Better	100/50000
11. Plaster Mold Casting (*)	Molten Ingot	Up to 15 dia in most materials common/200 dia or more 35" has been made	1/32" Sections possible	300 - 2000 pieces per pattern per week	Non-ferrous material	± .005" - ± .010"	125 Obtainable	>1000
12. Powder Metallurgy	Powder	Parts below 4 sqin are best, larger can be made	1/16" dia and some smaller	2 - 60 parts/minute	Iron, Brass, Combinations of Iron and Brass	± .0005" thru sizing. ± .001"-± .005" Common	63 and Better Obtainable	>10000

(*) For illustration purposes, these manufacturing processes are considered non-standard

TABLE 5. Machining Production Capabilities.
(Turning)

APPLICABLE PROCESS	SIZE MAXIMUM	SIZE MINIMUM	PRODUCTION RATE	MATERIAL CHOICE	TOLERANCE INCH	SURFACE ROUGHNESS micro inch	OPTIMUM LOT SIZE
1. Duplicating Lathe	32 in dia x 60 in long	1 in. dia x 5 in. long	40 pcs. per hour	All ferrous and non-ferrous non-hardened metals	± .002 - ± .003	90 - 250	100 - 10000
2 Multi-Spindle Vertical Chucking Machine	14 in dia x 14 in long	6 in dia x 3 in. long	8 to 75 pcs per hour	All ferrous and non-ferrous non-hardened metals	± .005	90 - 250	>50000
3 Single-Spindle Vertical Chucking Machine	17 in dia x 84 in. long	1/2 in dia x 4 in. long	2 to 150 pcs. per hour	All ferrous and non-ferrous non-hardened metals	± .002	90 - 250	>1000
4 Multi-Spindle Automatic Chucking Lathe	10 5/8 in dia x 6 in long	5/8 in dia x 2 1/4 in. long	9 to 600 pcs per hour	All ferrous and non-ferrous non-hardened metals	± .002 - ± .005	90 - 250	>10000
5 Numerical Controlled Lathe	8 1/2 in dia x 54 in long	1 in dia x 4 in. long	1 to 60 pcs. per hour	All ferrous and non-ferrous non-hardened metals	± .001	10 - 12	10 - 100
6. Vertical Turret Lathe	152 in dia x 88 in long	6 in dia x 3 in. long	6 pcs. per hour	All ferrous and non-ferrous non-hardened metals	± .002 - ± .010	90 - 250	<100
7. Single Spindle Automatic Screw Machine	5 3/4 in dia x 12 in long	1/16 in dia x 3/4 in long	36 to 4800 pcs per hour	All ferrous and non-ferrous non-hardened metals	± .002 - ± .0035	90 - 250	>10000
8. Multi-Spindle Automatic Screw Machine	7 3/4 in dia x 12 in long	1/16 in dia x 1 1/2 in. long	4 to 720 pcs. per hour	All ferrous and non-ferrous non-hardened metals	± .0035	90 - 250	>10000
9. Swiss Automatic Screw Machine	1 in dia x 6 in long	.010 dia x 1/4 in long	30 to 1,200 pcs per hour	All ferrous and non-ferrous non-hardened metals	± .0002 - ± .0004	12 - 16	>10000

TABLE 6. Machining Production Capabilities. (Milling)

APPLICABLE PROCESS	SIZE MAXIMUM	SIZE MINIMUM	PRODUCTION RATE	MATERIAL CHOICE	TOLERANCE INCH	SURFACE ROUGHNESS	OPTIMUM LOT SIZE
1. Turrett Milling Machine	9 in x 12 in. x 25 in.	1/16 dia x 3/8 in. lg	10 to 100 pcs. per hour	Ferrous and non-ferrous up to Rock. "C" 40	± .001 - ± .005	63 - 125	<100
2. Vertical Rotary Milling Machine	40 in. dia x 18 in. thick	2 in. x 2 in. x 2 in.	1 to 1,000 pcs. per hour	Ferrous and non-ferrous up to Rock. "C" 40	± .001 - ± .005	63 - 125	>50000
3. Precision Milling Machine	4 ft. x 4 ft. x 10 ft. lg	6 in. x 6 in. x 6 in.	1 to 30 pcs. per hour	Ferrous and non-ferrous up to Rock. "C" 40	± .0005 - ± .001	63	<100
4. Automatic Bar Stock Milling Machine	3 in. dia. x 9 in lg	1/2 in. dia. x 1 lg	50 to 300 pcs. per hour	Ferrous and non-ferrous up to Rock. "C" 40	± .001 - ± .005	63 - 125	>50000
5. Continuous Profile Milling Machine	2 in x 2 in x any length	1/2 in x 1/2 in. x any length	5 to 25 in. per min.	Ferrous and non-ferrous up to Rock. "C" 40	± .002 - ± .010	63 - 125	>50000
6. Template Controlled Horizontal Rise and Fall Milling Machine	3 ft x 3 ft. x 10 ft. lg	1/4 in. x 1/2 in. x 1 in. long	1 to 100 pcs per hour	Ferrous and non-ferrous up to Rock. "C" 40	± .001 - ± .005	63 - 125	100 - 10000
7. Horizontal Automatic Cycle Milling Machine	10 in x 10 in. x 24 in. thick	1/4 x 1/2 x 1 in. lg	1 to 100 pcs. per hour	Ferrous and non-ferrous up to Rock. "C" 40	± .001 - ± .005	63 - 125	100 - 10000
8. Numerical Controlled Horizontal Milling Machine	24 in x 24 in. x 28 in. thick	3 in. x 3 in. x 3 in.	1 to 20 pcs. per hour	Ferrous and non-ferrous up to Rock. "C" 40	± .001 - ± .005	63 - 125	10 - 100
9. Numerical Controlled Vertical Contour Milling Machine	4 ft x 5 ft. x 18 in. thick	10 in x 10 in. x 4 in.	1 to 10 pcs. per hour	Ferrous and non-ferrous up to Rock. "C" 40	± .001 - ± .005	63 - 125	10 - 100

TABLE 7. Machining Production Capabilities. (Drilling)

APPLICABLE PROCESS	SIZE MAXIMUM	SIZE MINIMUM	PRODUCTION RATE	MATERIAL CHOICE	TOLERANCE INCH	SURFACE ROUGHNESS micro inch	OPTIMUM LOT SIZE
1. Portable Drilling Machine	No Limit	Ability to hold	10 to 60 pcs. per hour	All ferrous and non-ferrous metals to Rock. "C" 35.	± .003 to ± .007 on dia ± 1/64 for location w/out jigs	90 - 190	<1000
2. Stand Type Drilling Machine	1 in dia drill to center of 20 in dia	Ability to hold	20 to 350 pcs. per hour	All ferrous and non-ferrous metals to Rock."C" 35	± .003 to ± .007 on dia. ± 1/64 for location w/out jigs	90 - 190	<1000
3. Column and Upright Drilling Machine	3 in dia drill to center of 30 in dia.	Ability to hold	10 - 360 pcs. per hour	All ferrous and non-ferrous metals to Rock. "C" 35.	± .003 to ± .007 on dia ± 1/64 for location w/out jigs	90 - 190	,1000
4. Gang Drilling Machine	Combined wgt of part & fixture usually less than 25 lbs	Ability to hold	10 - 150 pcs. per hour	All ferrous and non-ferrous metals to Rock. "C" 35.	± .002 to ± .005 for location	90 - 190	<100
5. Numerical Controlled Layout Drilling Machine	24 in x 120 in x 10 in	Any piece requiring multiple holes	10 - 60 pcs per hour	All ferrous and non-ferrous metals to Rock "C" 35.	± .001 to ± .005 for location	90 - 190	<100
6. Two-Way Horizontal Drilling Machine	24 in x 24 in x 48 in	Any piece requiring 1 or more holes in opposite faces	16 - 300 pcs. per hour	All ferrous and non-ferrous metals to Rock. "C" 35	± .002 for location using busing plate	90 - 190	>50000
7. Sensitive Drilling Machine	10 in x 12 in x 15 in	Ability to hold	10 - 500 pcs. per hour	All ferrous and non-ferrous metals to Rock. "C" 35.	± .002 for location with jig	90 - 190	<50000
8. Deep Hole Drilling Machine	2 3/8 in dia hole 13 in dia x 135 in long part	1/8 in dia hole 3/8 in dia x 3 in. long	1 - 360 pcs. per hour	All ferrous and non-ferrous metals to Rock. "C" 35	± .003 on 1/8 dia. hole proportionately greater for larger	10 - 32	Any
9. Numerical Controlled Turret Drilling Machine	40 in x 50 in. x 24 in.	Ability to hold	10 - 400 pcs. per hour	All ferrous and non-ferrous metals to Rock. "C" 35.	± .002 to ± .005 for location	90 - 190	10 - 100
10. Multiple Spindle Drilling Machine	36 in x 36 in x 36 in	Approx 3 in. dia	10 - 600 pcs. per hour	All ferrous and non-ferrous metals to Rock "C" 35.	± .002 for location using jib	90 - 190	>10000
11. Automatic Drilling Machine	Approx 36 in x 36 in x 36 in and larger	Approx. 3 in dia	60 - 2000 pcs	All ferrous and non-ferrous metals to Rock. "C" 35	± .002 for location using jib	90 - 190	>100000
12. Radial Drilling Machine	Will drill in area between 16 1/2 in rad & 144 in rad	Parts too heavy to position by hand	1 - 10 pcs per hour	All ferrous and non-ferrous metals to Rock. "C" 35.	± .002 to ± .005 for location using jib.	90 - 190	<100
13. Universal Head Radial Drilling Machine	See Remarks	Parts too heavy to position by hand	1 - 10 pcs. per hour	All ferrous and non-ferrous metals to Rock "C" 35	± .002 to ± .005 for location using jib.	90 - 190	<100

7.2.4 Producibility Assessment Knowledge Base. This Knowledge Base contains the logic necessary to represent the producibility assessment methodology.

For the purpose of the demonstration, all the functionality of the system is implemented in a system based on a set of decision rules while all the producibility engineering data are stored in separated databases. The system requires the definition of a set of decision rules to represent the logic involved in a producibility evaluation environment and the logic needed to control the evaluation methodology. As mentioned in Section 3.2, DPAS uses the WPIF and the ODPD values to perform its duties. The WPIF values that are stored as part of the producibility knowledge base are the same that were listed in Table 1. For "easy access," this Table is repeated below.

The definition of the logic needed to calculate the ODPD values is represented as a series of decision tables. Decision tables offer a number of advantages when used to represent a decision process. They use a standard format and handle combinations of conditions in a very concise manner. Tables 8 through 21 show the decision tables used in the Phase I of this project.

TABLE 1. Producibility Rating Factors.

FACTOR	WEIGHTED PRODUCIBILITY INFLUENCING FACTOR (WPIF)	OBSERVED DESIGN PRODUCTION DIFFICULTY (ODPD)
Tolerances and surface finish	10	ODPD (I)
Production Facilities	9	.
Material Availability	8	.
Machinability	7	Range For
Geometric Features	6	Each Factor
Tooling	5	.
Materials/Mfg. Process Compatibility	4	10 = The Worst
Technical Skills	3	0 = The Best
Assemblability	2	.
Drawing Specifications	1	.

TABLE 8. Tolerances (Inches).

Tolerances Range	ODPD
0.005 to 0.0059	10
0.006 to 0.0069	9
0.007 to 0.0079	8
0.008 to 0.0089	7
0.009 to 0.099	6
0.010 to 0.016	5
0.017 to 0.024	4
0.025 to 0.031	3
0.032 to 0.039	2
0.040 to 0.060	1

TABLE 9. Surface Finish (Micro Inches RMS)

Surface Finish Range	ODPD
<65	10
65 - 89	9
90 - 96	8
95 - 99	7
100 - 124	6
125 - 139	5
140 - 149	4
150 - 174	3
175 - 249	2
>250	1

TABLE 10. Production Facilities.

EVALUATION FACTOR	Wgt	Decision Rules 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Production Quantity	1	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	N
Availablty	2	Y	Y	Y	Y	N	N	N	N	Y	Y	Y	Y	N	N	N	N
Std.Process	3	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N
Design Spc	4	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
ODPD	/	0	4	3	7	2	6	5	9	1	5	4	8	3	7	6	10

TABLE 11. Material Availability.

EVALUATION FACTOR	Wgt	Decision Rules 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Qty. Requirements	1	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	N
# Suppliers >=3	2	Y	Y	Y	Y	N	N	N	N	Y	Y	Y	Y	N	N	N	N
Availability	3	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N
Strategic	4	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
ODPD	/	4	0	7	3	6	2	9	5	5	1	8	4	7	3	10	6

TABLE 12. Machinability.

Machinability Rate	ODPD
50 - 60	10
61 - 70	9
71 - 80	8
81 - 90	7
90 - 100	6
101 - 110	5
110 - 120	4
121 - 130	3
131 - 140	2
141 - 150	1

TABLE 13. Geometric Features.
(Holes)

EVALUATION FACTOR	Wgt	Decision Rules															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Standard Diameter	1	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	N
Depth <=3d	2	Y	Y	Y	Y	N	N	N	N	Y	Y	Y	Y	N	N	N	N
Single Diameter	3	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N
Thru	4	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
ODPD	/	0	4	3	7	2	6	5	9	1	5	4	8	3	7	6	10

TABLE 14. Geometric Features.
(Slots)

EVALUATION FACTOR	Wgt	Decision Rules 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Symmetric	1	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	N
Open	2	Y	Y	Y	Y	N	N	N	N	Y	Y	Y	Y	N	N	N	Y
Stepped	3	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N
Thru	4	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
ODPD	/	3	7	0	4	5	9	2	6	4	8	1	5	6	10	3	7

TABLE 15. Geometric Features.
(Cylindrical Surfaces)

EVALUATION FEATURE	ODPD
Single Outside Diameter	0
Two Outside Diameter	1
3 or more Outside Diameters	
Progressive Steps	
Stepped to One End	2
Stepped to Both Ends	
Increasing From Ends	3
Decreasing From Ends	4
Variable Steps	5
Tapered	
Single	2
Multiple	3

TABLE 16. Geometric Features. (Corner/Edge)

EVALUATION FEATURE	ODPD
Rabbet	1
Bevel	
Bevel 1	1
Bevel 2	2
Bevel 3	2
Chamfer	1
Fillet	
Fillet 1	2
Fillet 2	3
Fillet 3	4
Notch	
Notch 1	2
notch 2	3
Radius	
Radius 1	3
Radius 2	4
Radius 3	4
Radius 4	5
Radius 5	6

TABLE 17. Tooling.

EVALUATION LEVEL	ODPD
Simple or Minor Tooling	1
Moderate	4
Significant	8
Special, New Technology or Dedicated	10

TABLE 18. Material/Manufacturing Processes Compatibility.

EVALUATION FACTOR	ODPD
Compatibles	0
Non-Compatibles	10

TABLE 19. Technical Skills.

EVALUATION LEVEL	ODPD
Unskilled	1
Semi-Skilled	4
Trained on the Job	8
Specialist	10

TABLE 20. Assemblability.

EVALUATION FACTOR	Wgt	Decision Rules															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Component Symetry	1	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	N
Self-Guiding Features	2	Y	Y	Y	Y	N	N	N	N	Y	Y	Y	Y	N	N	N	N
Suitable for Automatic Orientation	3	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N
Suitable for Standard Assy. Equipment	4	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
ODPD	/	0	4	3	7	2	6	5	9	1	5	4	8	3	7	6	10

TABLE 21. Drawings Specifications.

EVALUATION FACTOR	Wgt	Decision Rules 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Complete Information	1	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	N
Follow Standards	2	Y	Y	Y	Y	N	N	N	N	Y	Y	Y	Y	N	N	N	N
Alternate Mtl/Mfg. Processes	3	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N
Documentation Process Restriction	4	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
ODPD	/	4	0	7	3	6	2	9	5	5	1	4	4	7	3	10	6

7.3 **<u>A Numerical Example</u>**. A simple example is presented here to illustrate the methodology. The shaft shown in Figure 7.1, with its associated design characteristics is the design alternative whose producibility is to be evaluated. It is assumed that the design characteristics listed in this example closely resemble a realistic design environment.

In order to assess the producibility of the given design, DPAS has access to an available list of Weighted producibility Influencing Factors (WPIF) and their values (Table 1). For the Observed Design Production Difficulty (ODPD), DPAS uses a series of producibility decision rules to question the user to assign an ODPD value that best reflects a particular design requirement. This value is based on provided user information regarding design specifications. As an illustration, the ODPD value for the material selection and availability attribute is explained here. A similar procedure is followed for each of the producibility assessment factors listed in Table 1.

The user inputs the type of material needed for the application as well as the basic size and shape of the product. With this information, DPAS consults its knowledge base and determines if the requested material is available in the quantity required. Next, DPAS determines if the material is available in the expected size and shape, if the number of suppliers for that material is three or more (it is assumed that an acceptable producibility policy is to have at least three suppliers for every material),

and if the material is labeled as strategic. Since every one of these 4 conditions requires a YES or NO answer, the number of possible combinations is 2^4 or 16 decision rules (Table 11). Only one of these rules will be triggered at a time when all its conditions are met. For example, when the first three conditions are given an affirmative answer and the requested material is non-strategic, the ODPD value is 0 according to Rule No. 2. Similarly, if the first three conditions get a negative answer and the selected material is considered strategic, the ODPD value (as determined by Rule No. 15) will be 10.

Rule 15 from Table 11 is read as follows:

R15: IF material quantity requirements are not met,
AND the number of suppliers is NOT at least 3,
AND the material is NOT available in the requested standard size and shape,
AND the material is considered strategic,

THEN the Observed Design Production Difficulty (ODPD) is 10

(The design has been penalized with:
1 point because of first condition,
2 points because of secord condition,
3 points because of third condition, and
4 points because of fourth condition
making the ODPD value as 1+2+3+4 = 10)

As can be seen in Table 10, the material selection and availability attribute is also rated based on four factors: The quantity requirements, the number of suppliers, the material availability in the requested size and shape, and the strategic condition of the material. Each one of these factors have been weighted according to its relative "production difficulty." In a simple schema, when the requested material is not available in the quantity needed, the design is considered to have a production difficulty of 1. Similarly, when the design requires a strategic material, the production difficulty is considered as 4.

Following a similar procedure for each producibility assessment factor listed in Table 1, the other ODPD values are calculated. These values are shown in Table 22. Therefore, the MI for the shaft is calculated as follows:

$$MI = \sum_{i=1}^{10} WPIF_i * ODPD_i$$

$$MI = 10*10 + 9*4 + 8*4 + 7*9 + 6*3 + 5*0 + 4*0 + 3*4 + 2*3 + 1*5$$

$$MI = 292$$

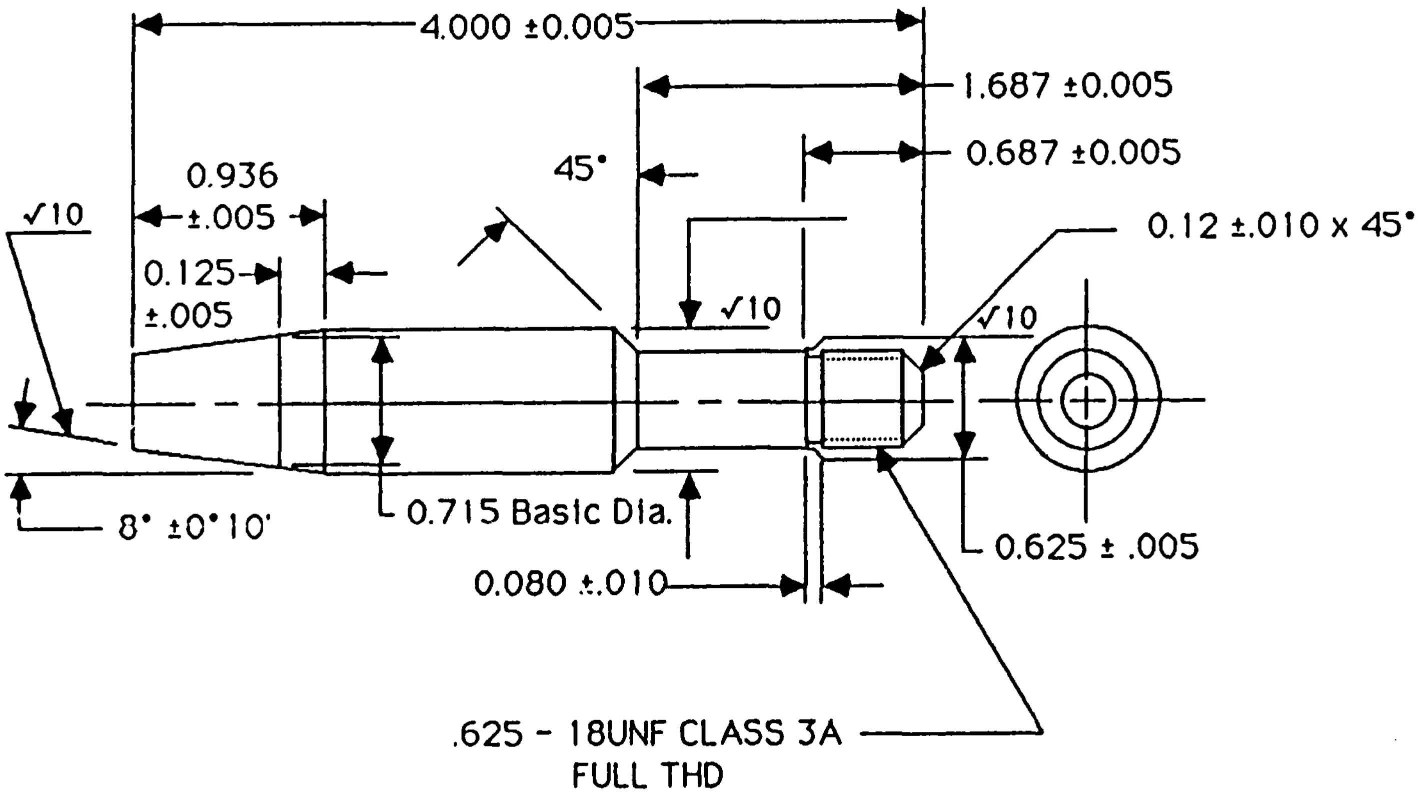
The MI value calculated using Equation No. 1 is meaningless without a proper interpretation. In order to provide the user with a point of reference on whether to accept or reject a product design, DPAS compares the computed MI value against the following threshold values.

Threshold Values

MI	Decision
0 - 100	Excellent (Accept)
101 - 200	Good (Accept)
201 - 300	Average (Review)
301 - 500	Poor (Redesign)
> 500	Unacceptable

Therefore, for the MI value (292) calculated in this example, DPAS concludes that the producibility level is just average recommending a detailed review of product design. Looking at the values corresponding to ODPD, it is noted that the tolerance and surface finish factor has been rated with 10 (the ODPD maximum value). This is because of the tight tolerances and the quality of surface finish required (0.005" and 10 micro inches RMS). In order to meet these design specifications, the shaft would require rough and finish grinding operations in addition to shaft-turning, forming and cutoff. Another factor that also increases significantly the MI value is the poor machinability of the suggested material (303 corrosion resistant steel). Its effect added to the level of tolerances and surface finish decreases the shaft level of producibility. The design finishing specifications also demand semi-skilled technical abilities as detected by DPAS by an ODPD value of 4 (from Table 19).

If the tolerances are changed to 0.040 inches, the surface finish is changed to 250 micro inches RMS and the material is replaced by the B1112 Cold-rolled steel leaving the other design characteristics unchanged, the new MI value will be 181. This value represent an improvement in the producibility of the design of about 38%. [The B1112 steel is appropriate when ease of machining and surface finish are of prime importance.]



MATERIAL: 303 CRES
FINISH: PASSIVATE
BATCH SIZE: 15,000 PARTS

NOTES:
REMOVE BURRS AND BREAK SHARP EDGES
0.005 MAX.

Figure 7.1. Example Part.

TABLE 22. **Producibility Rating Factors. (Numerical Example)**

FACTOR	WEIGHTED PRODUCIBILITY INFLUENCING FACTOR (WPIF)	OBSERVED DESIGN PRODUCTION DIFFICULTY (ODPD)
Tolerances and Surface Finish	10	10
Production Facilities	9	4
Material Availability	8	4
Machinability	7	9
Geometric Features	6	3
Tooling	5	4
Material/Mfg. Process Compatibility	4	0
Technical Skills	3	4
Assemblability	2	3
Drawing Specifications	1	0

7.4 __Demo Running Overview__. In order to interact with the DPAS demo, a few basic instructions are necessary. These include what to do, what to avoid doing and what to expect. Each of these will be explained as we go through a simple example.

7.4.1 Starting the Demo. To start the demo, set the default directory to point to the directory where DPAS is located and type DPAS<CR>. The program will begin to do its thing and, after a few seconds, the Introductory Screen (Figure 7.1) will appear. Note the header area at the top of the screen. This will always contain the title as well as the date and time. To continue, press <ESCAPE>. This will display the screen shown in Figure 7.2.

This is the top level menu screen. There are two things to note about this screen. The first is the message line at the bottom of the screen. This line will always contain information indicating which keys are valid at the current time. Also note the top level menubar immediately below the header area. This menubar is the beginning of DPAS. All DPAS functions are accessed from this point. Note that the current selection (the one that will be chosen if the enter key is pressed) is highlighted (in white for color monitors). To move between options, use the left and right arrow keys. To make a selection, press enter when the selection is highlighted. Note that each of the selections on the menubar has a pulldown menu that appears when that option is selected.

DPAS v1.00 Saturday June 17, 1989 9:48 am
Design Producibility Assessment System

Design Producibility Assessment System

DPAS is a software tool to assist design engineers in measuring design, material, and manufacturing factors as they relate to product manufacturability. Based on these factors the program produces a Manufacturability Index (MI), a measure of design producibility.
<Press ESCAPE to continue>

<Esc> Continue

Figure 7.1 __Introductory Screen__.

DPAS v1.00 Saturday June 17, 1989 10:30 am

Design Producibility Assessment System

Engineering Data Bases   Design Evaluation   Reports

<Enter> Select, <F1> Help, <Esc> Continue

Figure 7.2 <u>DPAS Top Level Menu</u>.

7.4.2 Engineering Data Bases. To start a session, you may either begin from scratch or you may restore the system to a prior state by loading a file containing previously stored information. To load values, select Engineering Data Bases by moving the highlight to it and pressing return. Then you will have the option to select the design, materials or manufacturing processes and the screen in Figure 7.3 will appear. To load information about a particular data base, use the up and down arrow keys (page up and page down also work) to position the highlight and press ENTER (see Figures 7.4 and 7.5).

DPAS v1.00 Saturday June 17, 1989 10:33 am

Design Producibility Assessment System

Engineering Data Bases Design Evaluation Reports

Engineering Data Bases

Design
Material
Manufacturing Processes

<Enter> Select, <F1> Help, <Esc> Continue

Figure 7.3 Engineering Data Bases.

```
DPAS  v1.00                               Saturday  June 17, 1989  10:43 am
                       Design Producibility Assessment System

Engineering Data Bases   Design Evaluation   Reports

 Engineering Data Bases

 |Design    |               Material Data Base
 |Material  | Code                 17-4PH
 |Manufactu | Description
            | Precipitation-Handling, corrosion-resist steel
            | Strategic?           No
            |  Strip     Sheet     Bar       Wire      Tube
            |   Yes       Yes      Yes       Yes       Yes
            | Num. of Suppliers: 4
            | Machinability        60


   <Ctrl PgUp> Previous Record <Ctrl PgDn> Next Record <F1> Help <Esc> Exit
```

Figure 7.4 <u>Material Data Base</u>.

```
DPAS  v1.00                               Saturday  June 17, 1989  10:45 am
                       Design Producibility Assessment System

Engineering Data Bases   Design Evaluation   Reports

 Engineerin
                              PrimProc Data Base
  Manufactu | Code                     01
            | Description  Extrusion
   |Primary | Standard?                Yes
   |Turning | Compatible?              Yes
   |Milling | Highest Tolerance        0.0050
   |Drilling| Finest Surface Finish    63
            | Highest Lot Size         -1
            | Lowest Lot Size          10000
            | (Infinite Highest Lot Size is indicated by -1)


   <Ctrl PgUp> Previous Record <Ctrl PgDn> Next Record <F1> Help <Esc> Exit
```

Figure 7.5 <u>Manufacturing Data Base</u>.

7.4.3 **Design Evaluation.** When you are ready to generate a Manufacturability Index (MI), select Design Evaluation from the menubar (Figure 7.6). This category is the top of a menu tree. Within this category will ultimately be all the necessary questions for generating a Manufacturability Index (MI) (currently only 10 screens of questions are implemented). Questions are grouped into screens and the screens are hooked into the menu tree where appropriate. Once an option from the pull down menu is chosen, it will in turn bring up another menu. This process will continue until a screen of questions appears (where the questions have actually been implemented).

DPAS v1.00 Saturday June 17, 1989 10:52 am

Design Producibility Assessment System

Engineering Data Bases Design Evaluation Reports

Assessment Factors	WPIF
Tolerances and Surface Finish	10
Production Facilities	9
Material Availability	8
Machinability	7
Geometric Features	6
Tooling	5
Mtl./Mfg. Proc. Compatibility	4
Technical Skills	3
Assemblability	2
Drawing Specifications	1

<Enter> Select, <F1> Help, <Esc> Continue

Figure 7.6 Producibility Assessment Factors.

7.4.4 Question Screen. Once you are on a question screen (Figure 7.7), note several things: 1) Up and down arrow keys move the highlight from question to question, as do the home and end keys. 2) Pressing enter once causes the highlighted question to become active. This means that the value can be edited. Alternatively, a new value can be entered directly into a highlighted field without pressing ENTER. To edit the active field, the backspace and delete keys can be used in their normal manner, as well as the left and right arrow keys to position the cursor in the highlighted field. 3) Press enter to exit a field that has been edited. Once all fields contain the desired values, you can exit the question screen by pressing ESCAPE. This process is repeated for all the Question Screens.

```
DPAS  v1.00                              Saturday  June 17, 1989  10:58 am
                 Design Producibility Assessment System

Engineering Data Bases   Design Evaluation   Reports

                    Assessment Factors              WPIF

                              Assemblability

          Is the part a symmetric component?                      No
          Are self-guided features included in the part design?   No
          Is the part suitable for automatic orientation?         Yes
          Is the part suitable for standard assembly equipment?   No

                     Assemblability                    2
                     Drawing Specifications            1

                       <F1> Help, <Esc> Continue
```

Figure 7.7 Questions Screen.

7.4.5 Getting Help. At any point, you may request help. Help is accessed by pressing <F1> at the point you need help. If on-line Help is available, it will be displayed. At this point the <PgUp> and <PgDn> keys will take you back and forth through all the Help screens for the topic at hand. Currently on-line Help is available for most of the screens. This Help screen was displayed from the Assembly Assessment Factor. An example of Help Screen is shown in Figure 7.8.

DPAS v1.00 Saturday June 17, 1989 11:01 am

Design Producibility Assessment System

Engineering Data Bases Design Evaluation Reports

ASSEMLABILITY

In the context of component producibility analysis, assemblability measurements are designed to consider the autonomus part only, without regard to its potential adjoining parts. Only those attributes that contribute to make the part itself easier to assemble such as symetricity (ability to assemble from either direction), compatibility with standard assembly equipment (auto-feedable, auto-insertable), and a number of other characteristics which would make the component being considered easier to assemble, are considered.

<Enter> Select, <F1> Help, <Esc> Continue

Figure 7.8 Help Screen.

7.4.6 Reports. Two reports are provided with the system (Figure 7.9). Both may be displayed on your screen or an attached parallel printer. One report is the Manufacturability Index (MI) Summary, a summary of the part design's manufacturability, along with the various design factors that make it up (Figure 7.10). The other report is the Part Description & ODPD detail. This is a listing of all the raw data you have entered to describe the design, along with the ODPD values calculated from it (Figure 7.11).

The last item on the Report menu is a form to change the WPIF values. This allows you to assign varying degrees of importance to the items influencing producibility. It affects the MI Summary report, but not the Part Description & ODPD detail report. These values may be changed here only for a single session. They are always reset to the default values when the program is started.

```
DPAS  v1.00                           Saturday  June 17, 1989   10:02 am
                    Design Producibility Assessment System

Engineering Data Bases   Design Evaluation   Reports

                                                  Reports
                                                  MI Summary Analysis
                                                  Part Detail
                                                  Change WPIF's

                  <Enter> Select, <F1> Help, <Esc> Continue
```

Figure 7.9 <u>Reports Screen.</u>

DPAS v1.00 Saturday June 17, 1989 10:57 am

Design Producibility Assessment System

Engineerin

MI Analysis Summary

Part Code/Number: P1

Description: Example part

Factor	WPIF	ODPD	Score	%
Tolerances and Surface Finish	10	10	100	31%
Production Facilities	9	5	45	13%
Material Availability	8	0	0	0%
Machinability	7	10	70	21%
Geometric Features	6	4	24	7%
Tooling	5	8	40	12%
Mtl./Mfg. Proc. Compatibility	4	0	0	0%
Technical Skills	3	8	24	7%
Assemblability	2	7	14	4%
Drawing Specifications	1	5	5	1%

Total MI = 322

Hit any key to continue.

s

Figure 7.10 <u>MI Analysis Screen.</u>

```
DPAS  v1.00                               Saturday  June 17, 1989  11:03 am
                    Design Producibility Assessment System
```

```
                     Part Description & ODPD Detail

Part Code/Number: P1
Description: Example part

Question/Title                                          Answer        ODPD
---------------------------------------------------------------------------
Enter the design tolerance (in.):                       0.0050
Enter the design surface finish (RMS):                  65
TOLERANCES AND SURFACE FINISH                                           10

Select the intended primary manufacturing process:      06
Select the intended secondary manufacturing process:    T1
Enter the planned production quantity:                  10000
PRODUCTION FACILITIES                                                    5

Select the design material:                             17-4PH
```

```
           <PgUp> Page Up, <PgDn> Page Down, <F1> Help, <Esc> Exit
```

```
DPAS  v1.00                               Saturday  June 17, 1989  11:06 am
                    Design Producibility Assessment System
```

```
Select the design material:                             17-4PH
Select the design material's form:                      Bar
MATERIAL AVAILABILITY                                                    0

MACHINABILITY                                                           10

Enter the hole diameter size (in.):                     1.7500
Enter the hole depth (in.):                             0.5000
Is the part feature a single hole diameter ?            Yes
Is the part feature a through hole ?                    No
Hole                                                               5

Is the part feature a symmetric slot ?                  Yes
Is the part feature an open slot ?                      Yes
Is the part feature a stepped slot ?                    Yes
Is the part feature a through slot ?                    No
Slot                                                               7
```

```
           <PgUp> Page Up, <PgDn> Page Down, <F1> Help, <Esc> Exit
```

Figure 7.11 Part Detail.

Figure 7.11 Continued on Next Page

```
DPAS  v1.00                               Saturday  June 17, 1989  11:08 am
                    Design Producibility Assessment System
```

```
Select the type of cylindrical surface on the part:
                                           Steps increasing from the ends
Cylindrical Surface                                               3
Select the type of corner/edge feature of the part:    Chamfer
Corner Edge Feature                                               1
GEOMETRIC FEATURES                                                    4

Select the tooling requirements for the part:          Significant
TOOLING                                                               8

MTL./MFG. PROC. COMPATIBILITY                                         0

Select the level of required technical skills:         Trained on the job
TECHNICAL SKILLS                                                      8

Is the part a symmetric component?                     No
Are self-guided features included in the part design?  No
```

<PgUp> Page Up, <PgDn> Page Down, <F1> Help, <Esc> Exit

```
DPAS  v1.00                               Saturday  June 17, 1989  11:13 am
                    Design Producibility Assessment System
```

```
MTL./MFG. PROC. COMPATIBILITY                                         0

Select the level of required technical skills:         Trained on the job
TECHNICAL SKILLS                                                      8

Is the part a symmetric component?                     No
Are self-guided features included in the part design?  No
Is the part suitable for automatic orientation?        Yes
Is the part suitable for standard assembly equipment?  No
ASSEMBLABILITY                                                        7

Is the drawing information package complete?           Yes
Does the drawing follow standards?                     No
Does the drawing include alternate materials & mfg. processes?
                                                       No
Does the drawing imply process restriction?            No
DRAWING SPECIFICATIONS                                                5
```

<PgUp> Page Up, <PgDn> Page Down, <F1> Help, <Esc> Exit

Figure 7.11 Continued From Previous Page
Figure 7.11 Part Detail.

7.4.7 Getting Out. Once you are finished with the demo, use the ESCAPE key to back up and out of the program. Each time you press ESCAPE, you will back up one menu level until you reach the initial menubar. At this point, press ESCAPE and the screen in Figure 7.12 will appear. Select "Yes" to exit the system.

DPAS v1.00 Saturday June 17, 1989 11:17 am

Design Producibility Assessment System

Engineering Data Bases Design Evaluation Reports

Exit DPAS

No

Yes

<Enter> Select, <F1> Help, <Esc> Continue

Figure 7.12 Exit Screen.

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APPENDIX A
AN OVERVIEW OF PRODUCIBILITY ASSESSMENT TOOLS

Consideration of the state of the art during Phase I of this project is necessary for two reasons. First, it allows one to determine more accurately what the needs are by evaluating what similar problems others have tried to solve. Second, it allows one to establish the conditions and criteria needed to solve a problem. For the DPAS project the main concern is the definition of simple and objective measures of producibility.

In the last decade, a great deal of effort has been devoted to the development of simple and easy to use methods of evaluating producibility. Although some progress have been made in the subject, a universally accepted methodology has not been developed.

There are basically two approaches for producibility assessment which are recognized as being of practical value. These are: Qualitative Design Rules and Producibility Rating Systems (Priest 1988).

Qualitative Design Rules. The first approach to measure producibility is to develop lists of qualitative or quantitative design rules. For many companies these rules are organized and published as "design guidelines" or "design recommendations" (Bralla 1986, Boltz 1977, and Bellows 1976). Although this type of guidelines are useful for some design cases, they can quickly become obsolete as new technologies are introduced. Another drawback of this approach is that most of them are proprietary and not available for public use (Boothroyd and Dewhurst 1986, General Electric 1981, Rockwell International 1977). Other producibility systems available today are also limited in scope. For example, there are systems available for assembly (Boothroyd and Dewhurst 1986), for N/C production (Harrington 1980) or for aerospace materials (Howe 1968). While these are obviously useful for particular purposes, they are not suitable for general use. A final problem with design guidelines is that some of them are not organized in such a way as to be adaptable to computer processing. An example of such a system is the "Manufacturing Producibility Handbook" developed by General Electric (General Electric 1960).

Another approach used for producibility assessment is the development of an intelligent database or expert system. This approach uses design principles in a computer system to ensure producibility. An example of this type of approach is the Printed Control Board (PCB) Expert System for Producibility (ESP) developed by Texas Instruments, Inc. (Priest 1988). Its main objectives are to evaluate and rate board designs on manufacturability and to provide design recommendations that optimize fabrication and assembly. Using a Texas Instruments Personal Consultant computer, the model initially consisted of 216 combined rules, 137 parameters, and 1720 lines of user-written IQLISP code. User-written

code provided additional features to the expert system, such as iteration, printed reports, multiple recommendations, and rules. A feasibility model was tested against prior, producibility problems. Because of the eventual size for the knowledge base, information was grouped into five domain areas: components selection, placement plot, raw board, routing and documentation. When the system is completely finished, the knowledge base is expected to grow to approximately 1500 rules. This expert system parallels the design flow, allowing real-time iterative design analysis by showing an engineer how a change in the board design could affect the manufacturability of the board. This system is proprietary and not available for public use.

Producibility Rating Systems. The second approach to assess design producibility is to develop quantifiable rating systems to measure and rate the producibility of a given design. The most well-known rating systems are the Assemblability Evaluation Method developed by Hitachi and modified by General Electric (General Electric 1981) and the Design for Assembly method developed by Boothroyd and Dewhurst (Boothroyd 1986). Unfortunately, these particular systems are copyrighted. These systems are very effective for high volume mechanical assemblies and used by many companies. Portions of similiar types of systems are expected to be implemented in the second phase of this project. Another method that has been developed is a statistical algorithm that measures producibility as a function of design Robustness (Harry 1989). This method considers design robustness as a measure of design insensitivity to variations in materials, processes, methods and customer needs. Robustness is therefore quantified as the ratio of long term to short term process variations.

Two producibility rating systems have been identified by the development team. One is the input product manufacturing method, and the other, which can be called the empirical method, is discussed in detail in this report (Section 3.2).

The Input Product Manufacturing Method. Input product manufacturing depends not only on the design, but to a great extent on the planned manufacturing processes, its tooling, and the selected machining variables. Therefore, to evaluate the producibility of a design, it is necessary to exclude the influence of the adopted manufacturing process. Under these circumstances, the producibility of a given design can be expressed as the ratio of the input manufacturing required for its fabrication to that required for other design versions under similar or comparable production conditions.

If the producibility of two design versions is denoted by P_I and P_{II}, and the input manufacturing required of its fabrication under comparable production conditions by M_I and M_{II}, then

$$\frac{P_1}{P_2} = \frac{M_1}{M_2} \text{ or } P_1 = RP_2$$

where $R = \frac{M_1}{M_2}$ is the producibility ratio of the two design versions.

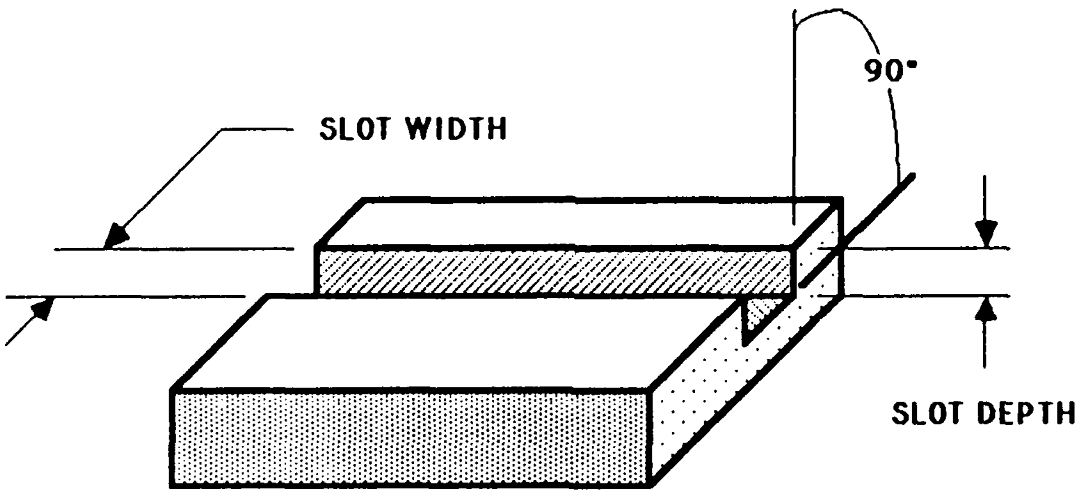
When $R > 1$, design 1 will be more producible than design 2 and vice versa when $R < 1$. Design 1 would be as producible as design 2 when $R = 1$.

Although this approach allows the numerical comparison of the producibility of two or more design alternatives, its major disadvantage is that the total input manufacturing required for a given design can only be estimated once its final design has been made.

APPENDIX B

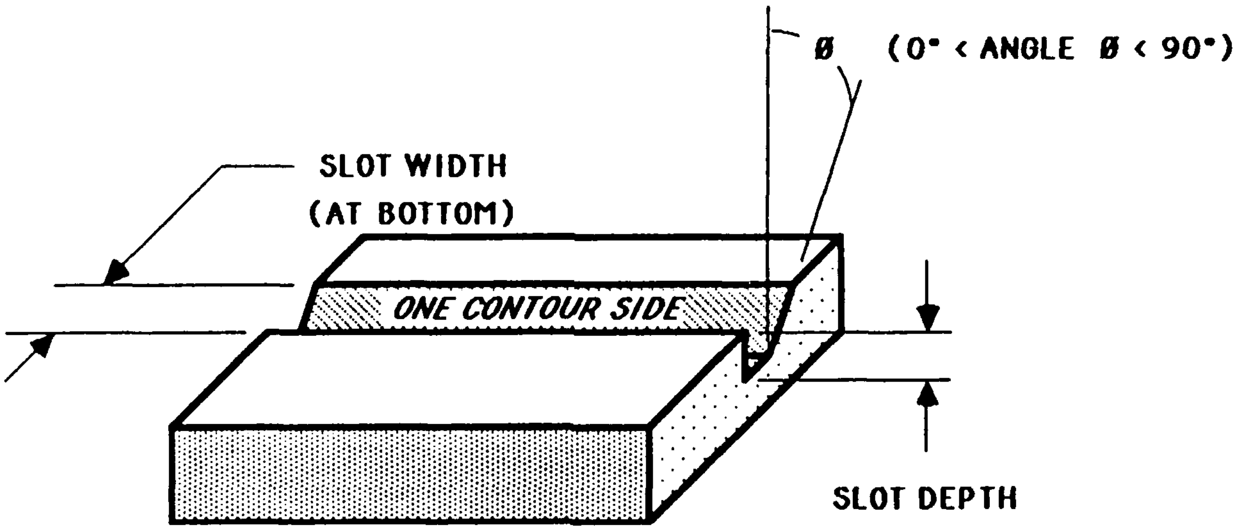
THE GEOMETRIC FEATURES LIBRARY

SIMPLE SLOT FEATURES

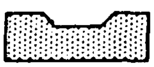


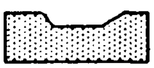
SHOWN 1.1.1.1 SLOT (VERTICAL SIDES)

SIMPLE SLOT FEATURES

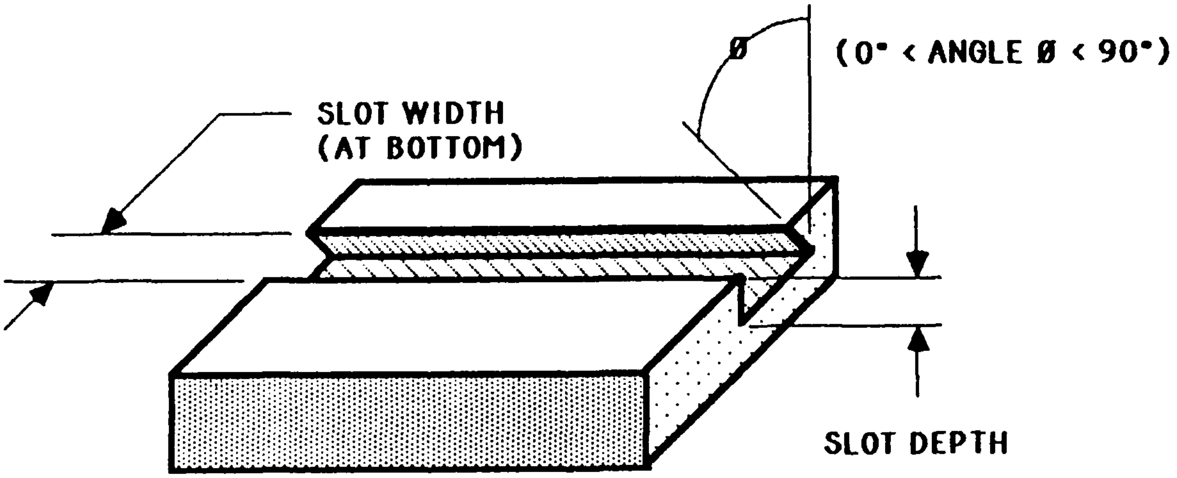


SHOWN 1.1.2.1 OPEN SLOT (1 CONTOUR SIDE)

 1.1.2.2 OPEN SLOT; SYMETRIC (2 EQUAL SIDE CONTOURS)

 1.1.2.3 OPEN SLOT; ASSYMETRIC (2 DIFFERENT SIDE CONTOURS)

SIMPLE SLOT FEATURES

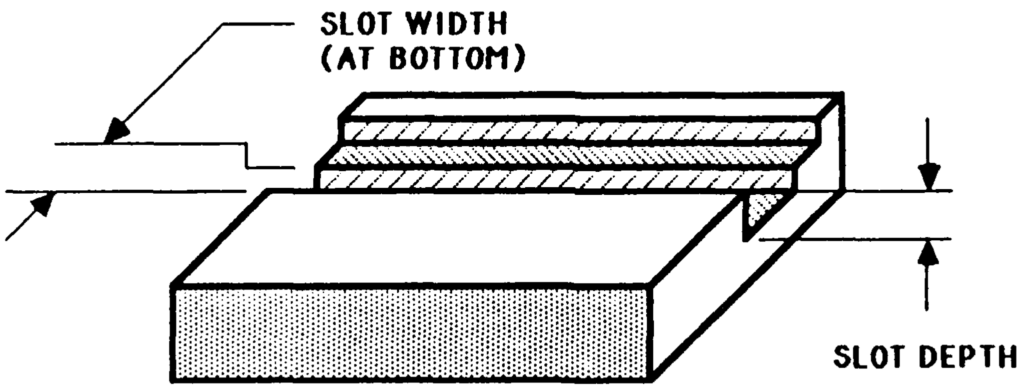


SHOWN 1.1.3.1 CLOSED SLOT (1 CONTOUR SIDE)

 1.1.3.2 CLOSED SLOT; SYMETRIC (2 EQUAL SIDE CONTOURS)

 1.1.3.3 CLOSED SLOT; ASSYMETRIC (1 OR MORE NON-EQUAL SIDE CONTOURS)

COMPLEX SLOT FEATURES



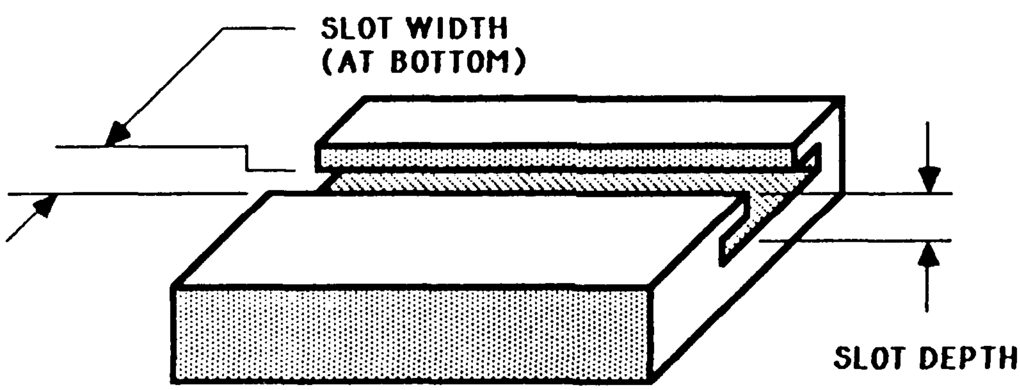
SHOWN 1.1.4.1.1 OPEN STEPPED SLOT; ASSYMETRIC (ALL VERTICAL SIDES)

 1.1.4.1.2 OPEN STEPPED SLOT; SYMETRIC (ALL VERTICAL SIDES)

 1.1.4.1.3 OPEN STEPPED SLOT; SYMETRIC(1 OR MORE OPEN SIDE CONTOUR)

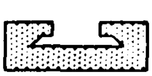
 1.1.4.1.4 OPEN STEPPED SLOT; ASSYMETRIC (1 OR MORE OPEN SIDE CONTOUR)

COMPLEX SLOT FEATURES



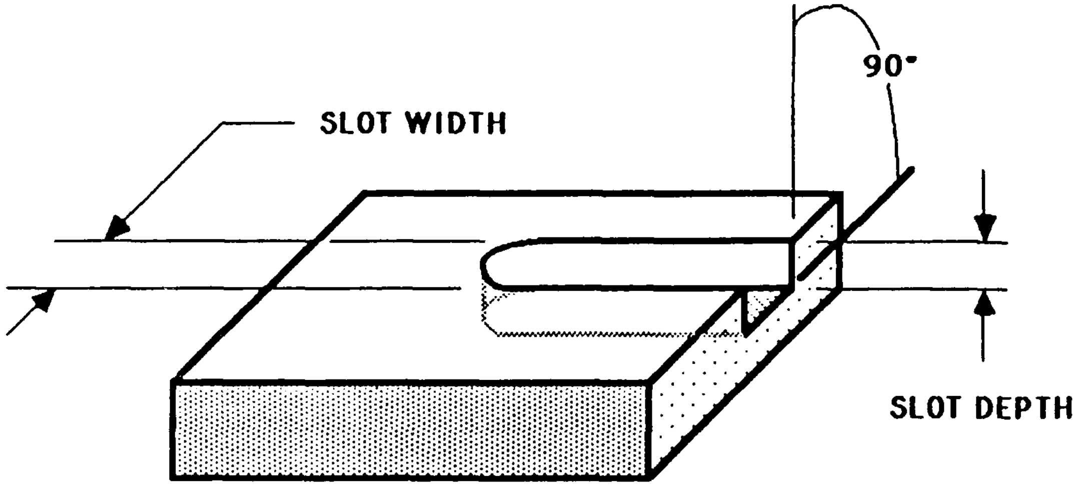
SHOWN 1.1.4.2.1 CLOSED STEPPED SLOT; SYMETRIC (ALL VERTICAL SIDES)

 1.1.4.2.2 CLOSED STEPPED SLOT; ASSYMETRIC (ALL VERTICAL SIDES)

 1.1.4.2.3 CLOSED STEPPED SLOT; SYMETRIC(EQUAL CONTOUR SIDE PAIRS)

 1.1.4.2.4 CLOSED STEPPED SLOT; ASSYMETRIC (ONE OR MORE SIDE CONTOURS)

BLIND SLOT FEATURES



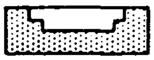
SHOWN 1.1.5.1 BLIND SIMPLE SLOT (VERTICAL SIDES)

 1.1.5.2 BLIND SIMPLE OPEN SLOT; SYMETRIC, CONCAVE BOTTOM

 1.1.5.3 BLIND SIMPLE OPEN SLOT; ASSYMETRIC (2 ≠ SIDE CONTOURS)

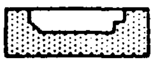
 1.1.5.4 BLIND SIMPLE CLOSED SLOT; SYMETRIC, CONCAVE BOTTOM

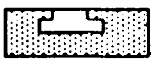
 1.1.5.5 BLIND SIMPLE CLOSED SLOT; ASSYMETRIC (2 ≠ SIDE CONTOURS)

 1.1.5.6 BLIND COMPLEX OPEN SLOT; SYMETRIC (ALL VERTICAL SIDES)

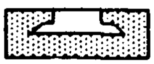
 1.1.5.7 BLIND COMPLEX OPEN SLOT; ASSYMETRIC (ALL VERTICAL SIDES)

 1.1.5.8 BLIND COMPLEX OPEN SLOT; SYMETRIC (1 OR MORE NON-VERT SIDE)

 1.1.5.9 BLIND COMPLEX OPEN SLOT; ASSYMETRIC (1 OR MOVE NON-VERT SIDES)

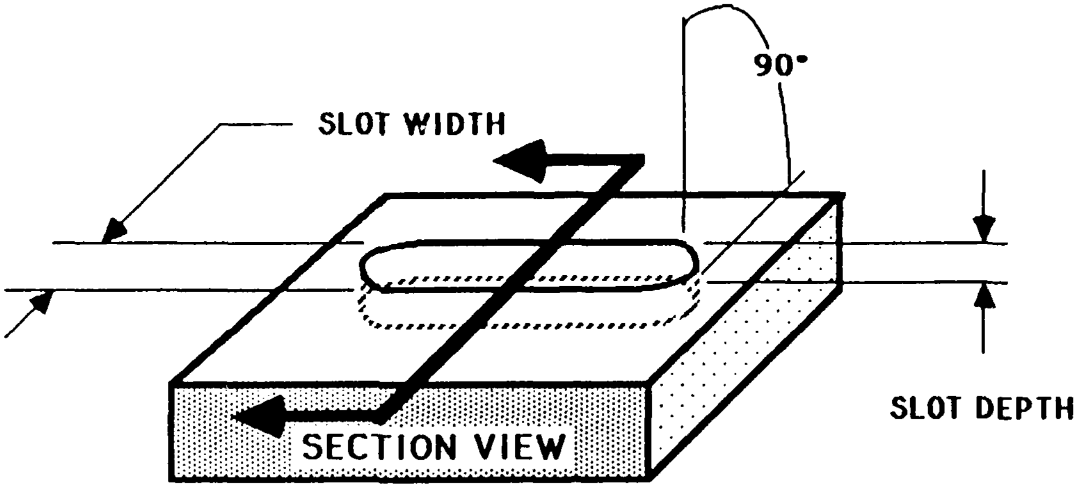
 1.1.5.10 BLIND COMPLEX CLOSED SLOT; SYMETRIC (ALL VERTICAL SIDES)

 1.1.5.11 BLIND COMPLEX CLOSED SLOT; ASSYMETRIC (ALL VERTICAL SIDES)

 1.1.5.12 BLIND COMPLEX CLOSED SLOT; SYMETRIC (1 OR MORE ≠ VERT SIDES)

 1.1.5.13 BLIND COMPLEX CLOSED SLOT; ASSYMETRIC (1 OR MORE ≠ VERT SIDES)

PLUNGE SLOT FEATURES

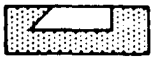


SHOWN 1.1.6.1 PLUNGE SIMPLE SLOT (VERTICAL SIDES)

 1.1.6.2 PLUNGE SIMPLE OPEN SLOT; SYMETRIC, CONCAVE BOTTOM

 1.1.6.3 PLUNGE SIMPLE OPEN SLOT; ASSYMETRIC (2 ≠ SIDE CONTOURS)

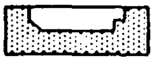
 1.1.6.4 PLUNGE SIMPLE CLOSED SLOT; SYMETRIC, CONCAVE BOTTOM

 1.1.6.5 PLUNGE SIMPLE CLOSED SLOT; ASSYMETRIC (2 ≠ SIDE CONTOURS)

 1.1.6.6 PLUNGE COMPLEX OPEN SLOT; SYMETRIC (ALL VERTICAL SIDES)

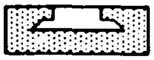
 1.1.6.7 PLUNGE COMPLEX OPEN SLOT; ASSYMETRIC (ALL VERTICAL SIDES)

 1.1.6.8 PLUNGE COMPLEX OPEN SLOT; SYMETRIC (1 OR MORE NON-VERT SIDE)

 1.1.6.9 PLUNGE COMPLEX OPEN SLOT; ASSYMETRIC (1 OR MOVE NON-VERT SIDES)

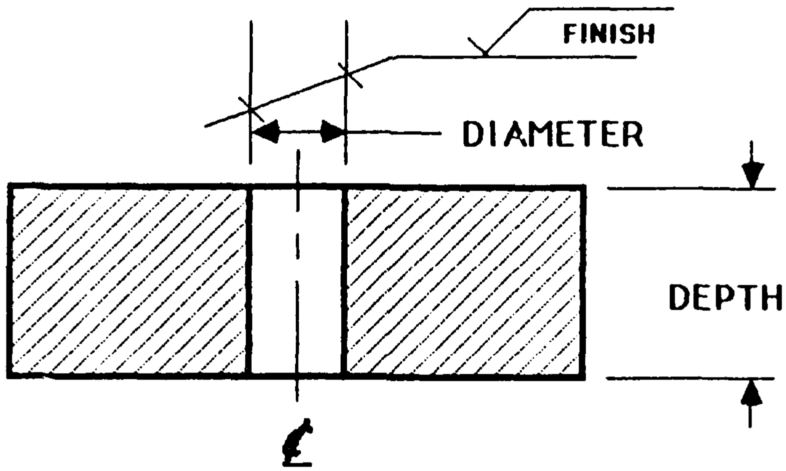
 1.1.6.10 PLUNGE COMPLEX CLOSED SLOT; SYMETRIC (ALL VERTICAL SIDES)

 1.1.6.11 PLUNGE COMPLEX CLOSED SLOT; ASSYMETRIC (ALL VERTICAL SIDES)

 1.1.6.12 PLUNGE COMPLEX CLOSED SLOT; SYMETRIC (1 OR MORE ≠ VERT SIDES)

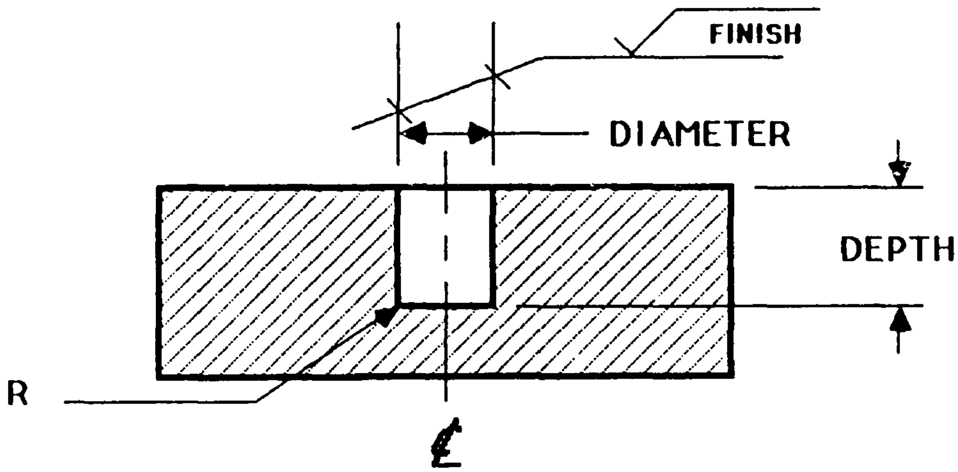
 1.1.6.13 PLUNGE COMPLEX CLOSED SLOT; ASSYMETRIC (1 OR MORE ≠ VERT SIDES)

SIMPLE HOLE FEATURES



SHOWN THRU HOLE

SIMPLE HOLE FEATURES

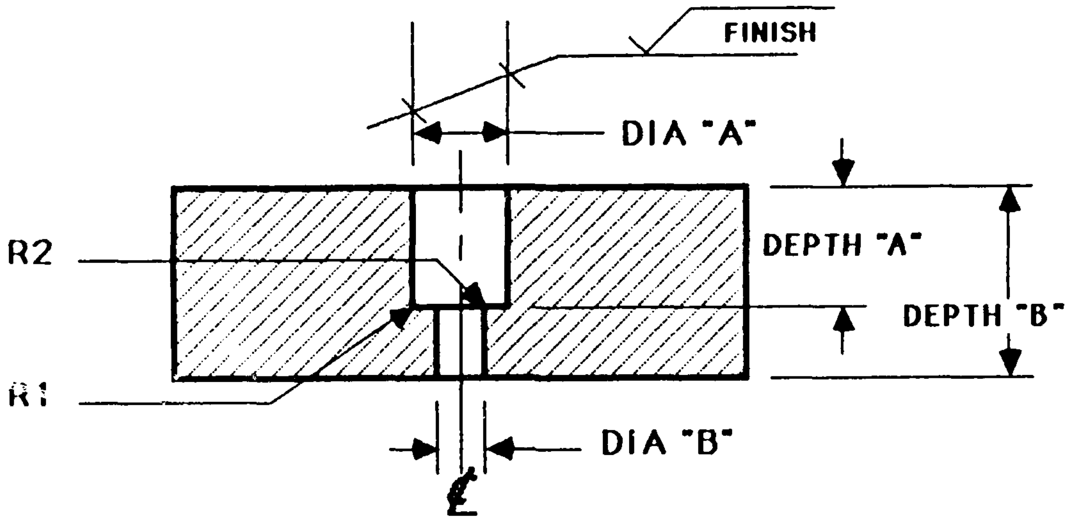


SHOWN BLIND HOLE (SQUARE BOTTOM)

 BLIND HOLE (DRILLED BOTTOM)

 BLIND HOLE (CONTOUR BOTTOM)

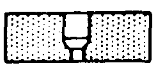
SIMPLE HOLE FEATURES



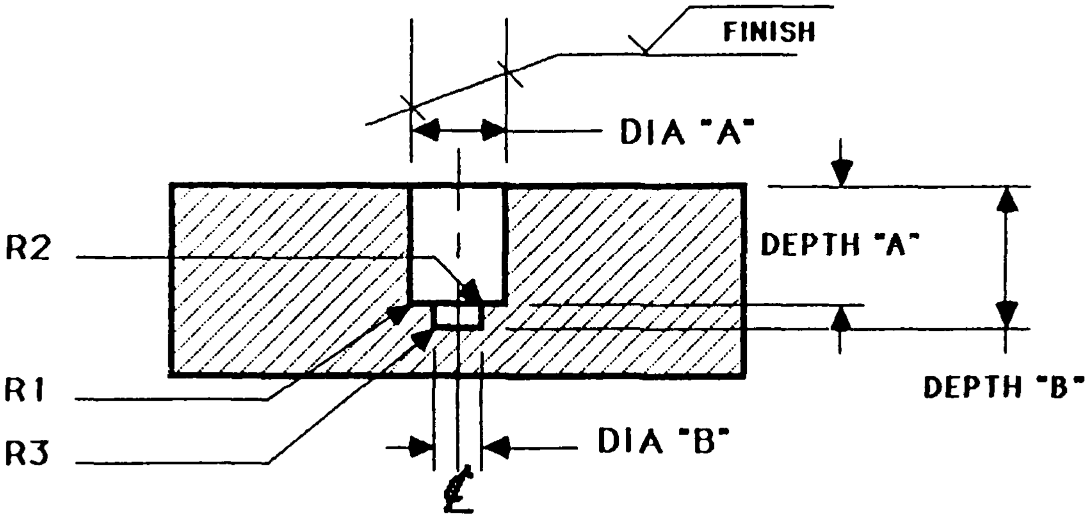
SHOWN STEPPED HOLE (COUNTERBORE)

 STEPPED HOLE (SPOTFACE)

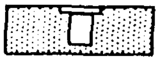
 STEPPED HOLE (DRILL STEP)

 STEPPED HOLE (CONTOUR)

COMPLEX HOLE FEATURES

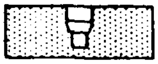


SHOWN BLIND (SQUARE BOTTOM), STEPPED (COUNTERBORE) HOLE

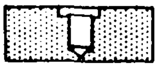
 BLIND (SQUARE BOTTOM), STEPPED (SPOTFACE) HOLE

 BLIND (SQUARE BOTTOM), STEPPED (DRILL STEP) HOLE

 BLIND (SQUARE BOTTOM), STEPPED (COUNTERSINK) HOLE

 BLIND (SQUARE BOTTOM), STEPPED (CONTOUR) HOLE

 BLIND (DRILLED BOTTOM), STEPPED (COUNTERBORE) HOLE

 BLIND (DRILLED BOTTOM), STEPPED (SPOTFACE) HOLE

 BLIND (DRILLED BOTTOM), STEPPED (DRILL STEP) HOLE

 BLIND (DRILLED BOTTOM), STEPPED (COUNTERSINK) HOLE

 BLIND (DRILLED BOTTOM), STEPPED (CONTOUR) HOLE

 BLIND (CONTOUR BOTTOM), STEPPED (COUNTERBORE) HOLE

 BLIND (CONTOUR BOTTOM), STEPPED (SPOTFACE) HOLE

 BLIND (CONTOUR BOTTOM), STEPPED (DRILL STEP) HOLE

 BLIND (CONTOUR BOTTOM), STEPPED (COUNTERSINK) HOLE

 BLIND (CONTOUR BOTTOM), STEPPED (CONTOUR) HOLE

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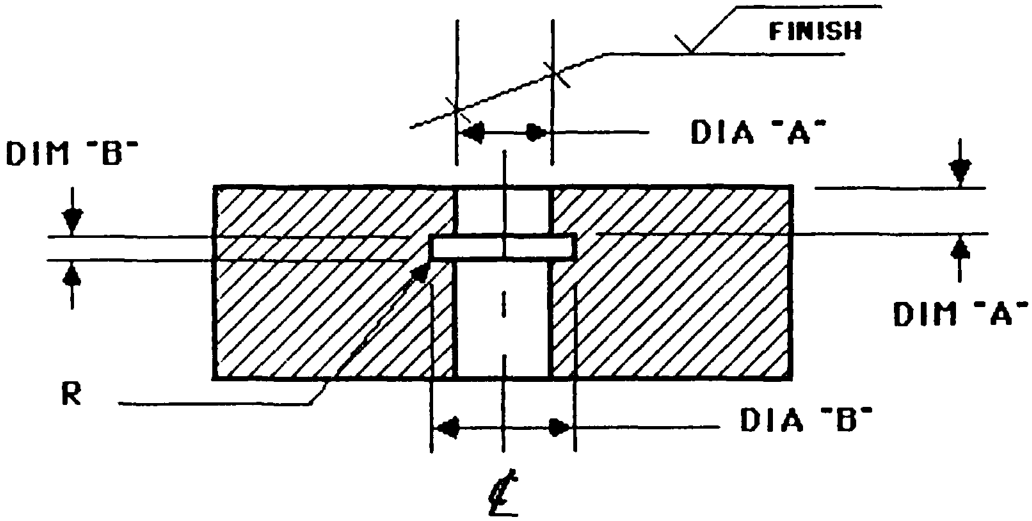
COMPLEX HOLE FEATURES



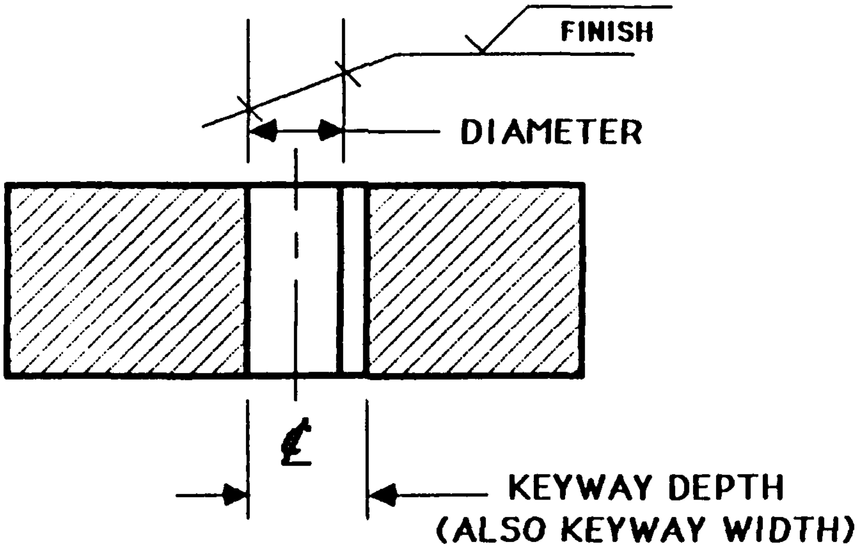
SHOWN INTERNAL GROOVE (SQUARE) IN HOLE

 INTERNAL GROOVE (OPEN CONTOUR) IN HOLE

 INTERNAL GROOVE (CLOSED CONTOUR) IN HOLE

 INTERNAL GROOVE (SPIRAL OIL GROOVE) IN HOLE

COMPLEX HOLE FEATURES

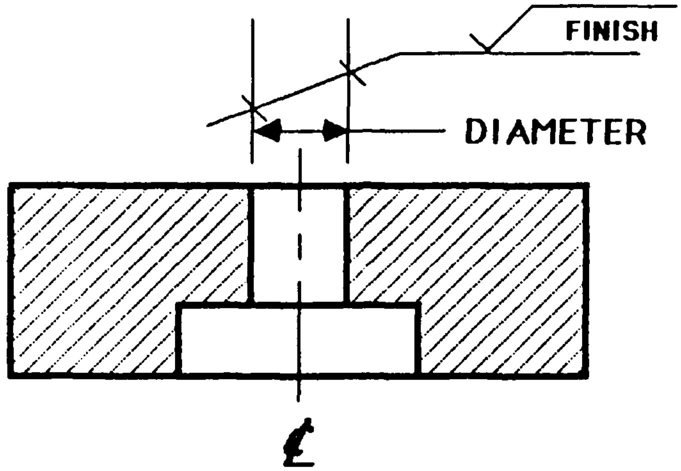


SHOWN INTERNAL KEYWAY

 INTERNAL POLYGON (SQUARE, HEX, ETC.)

 INTERNAL SPLINE

COMPLEX HOLE FEATURES



SHOWN REVERSE COUNTERBORE

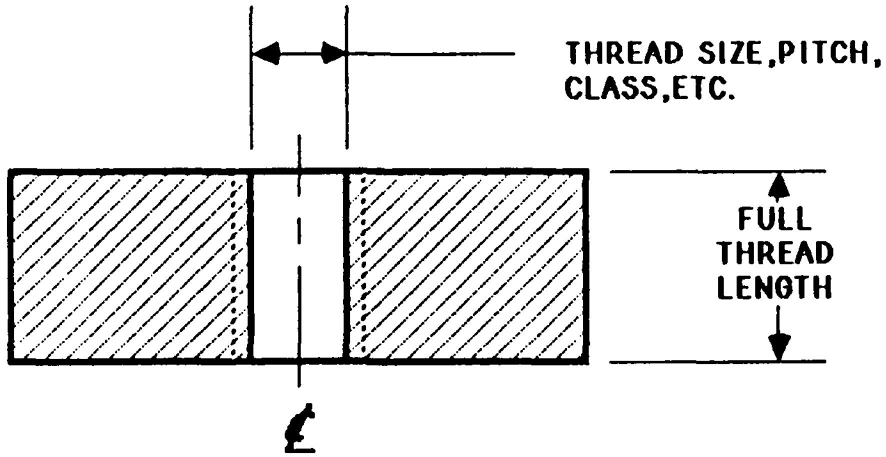
 REVERSE SPOTFACE

 REVERSE COUNTERSINK

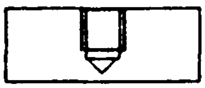
 REVERSE DRILL STEP

 REVERSE CONTOUR STEP

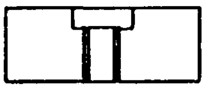
COMPLEX HOLE FEATURES



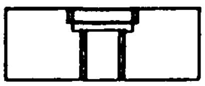
SHOWN FULLY THREADED HOLE



BLIND THREADED HOLE

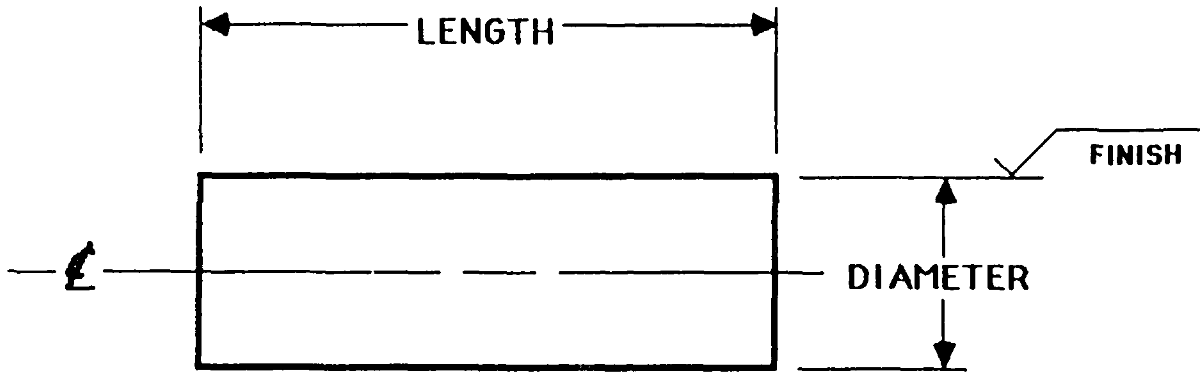


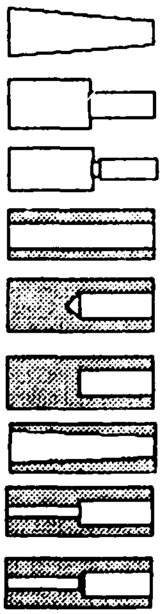
STEPPED THREADED HOLE



MULTI THREADED HOLE

SIMPLE SHAFT FEATURES





SHOWN PLAIN SHAFT

TAPERED SHAFT O.D. (CONICAL)

SQUARE STEPPED SHAFT

SQUARE UNDERCUT STEPPED SHAFT

HOLLOW SHAFT (THRU HOLE)

BLIND DRILLED HOLE SHAFT

BLIND BORED HOLE SHAFT

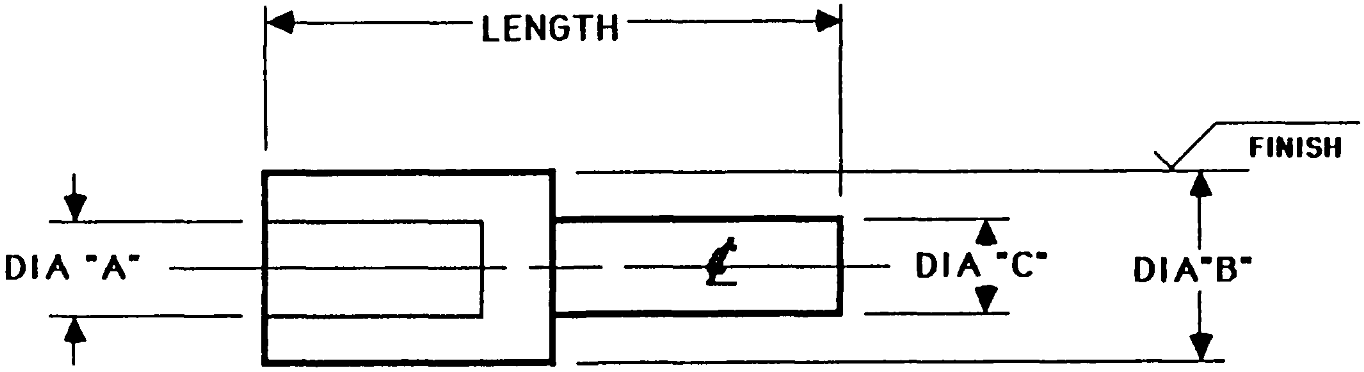
TAPERED HOLE SHAFT

SQUARE STEPPED HOLE SHAFT

DRILL STEPPED HOLE SHAFT

COMPLEX SHAFT FEATURES

(n = 2 COMBINATION OF SIMPLE SHAFT FEATURES)

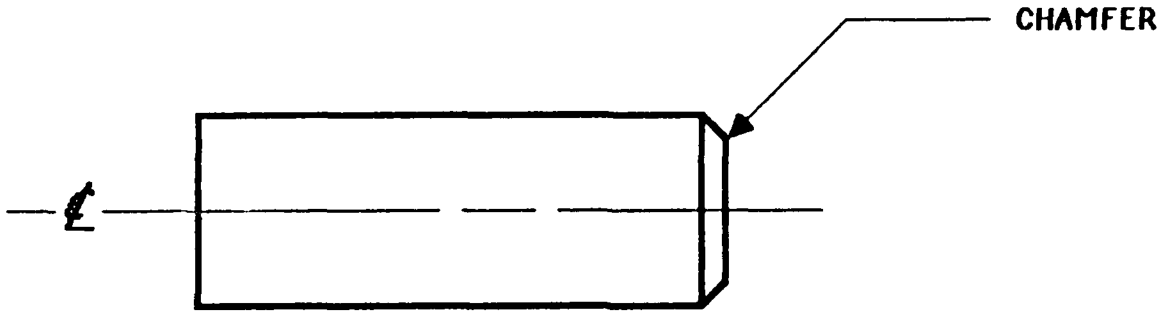


SHOWN TYPE 26 COMPLEX SHAFT WITH SQUARE STEPPED + BLIND BORED HOLE

TABLE OF COMPLEX SHAFT COMBINATIONS (n = 2)

TYPE XX	PLAIN	TAPERED O.D.	SQ.STEPPED	SQ STEP U/CUT	THRU HOLE	BLIND DRILL HOLE	BLIND BORE HOLE	TAPERED HOLE	SQ STEP HOLE	DRILL STEP HOLE
PLAIN		01	02	03	04	05	06	07	08	09
TAPERED O.D.	10	11	12	13	14	15	16	17	18	19
SQ.STEPPED	20	21	22	23	24	25	26	27	28	29
SQ STEP U/CUT	30	31	32	33	34	35	36	37	38	39
THRU HOLE	40	41	42	43	44	45	46	47	48	49
BLIND DRILL HOLE	50	51	52	53	54	55	56	57	58	59
BLIND BORE HOLE	60	61	62	63	64	65	66	67	68	69
TAPERED HOLE	70	71	72	73	74	75	76	77	78	79
SQ STEP HOLE	80	81	82	83	84	85	86	87	88	89
DRILL STEP HOLE	90	91	92	93	94	95	96	97	98	99

SUBSEQUENT SHAFT FEATURES



SHOWN EXTERNAL PRIMARY CHAMFER

 EXTERNAL SECONDARY CHAMFER

 EXTERNAL PRIMARY RADIUS

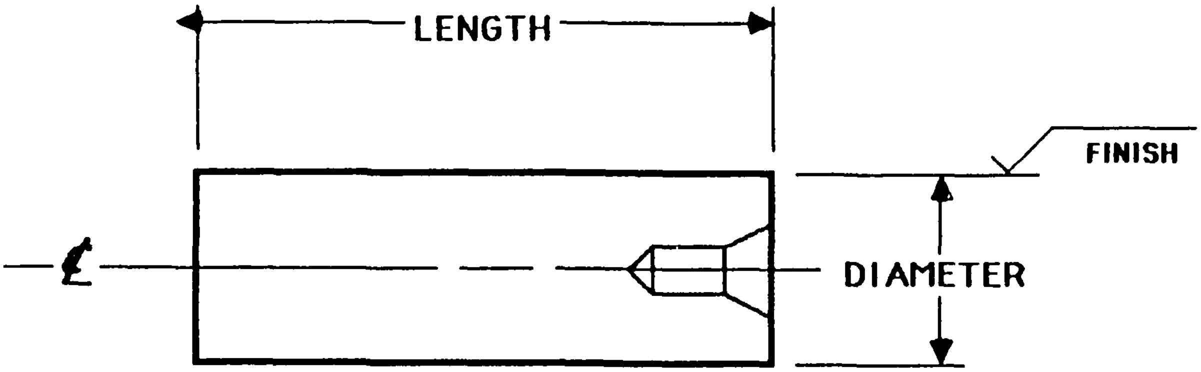
 EXTERNAL SECONDARY RADIUS

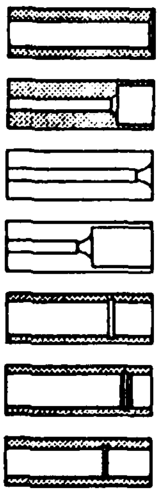
 EXTERNAL SQUARE ANNULAR GROOVE

 EXTERNAL OPEN ANNULAR GROOVE

 EXTERNAL CLOSED ANNULAR GROOVE

SUBSEQUENT SHAFT FEATURES





SHOWN CENTER DRILL

INTERNAL PRIMARY CHAMFER

INTERNAL SECONDARY CHAMFER

INTERNAL PRIMARY RADIUS

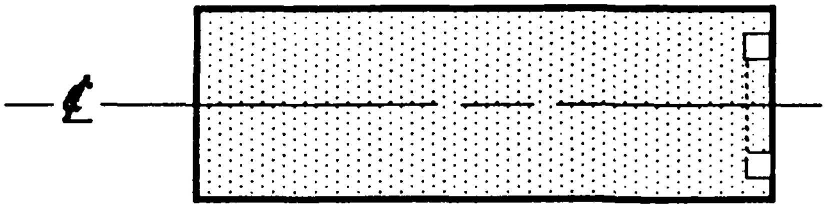
INTERNAL SECONDARY RADIUS

INTERNAL SQUARE ANNULAR GROOVE

INTERNAL OPEN ANNULAR GROOVE

INTERNAL CLOSED ANNULAR GROOVE

SUBSEQUENT SHAFT FEATURES

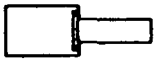


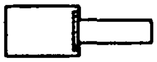
SHOWN EXTERNAL PRIMARY END GROOVE (SQUARE)

 EXTERNAL PRIMARY END GROOVE (OPEN)

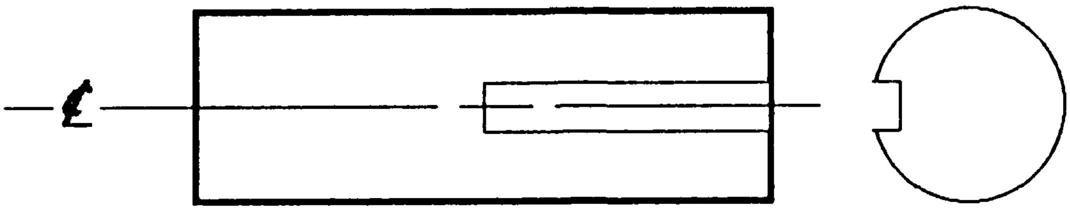
 EXTERNAL PRIMARY END GROOVE (CLOSED)

 EXTERNAL SECONDARY END GROOVE (SQUARE)

 EXTERNAL SECONDARY GROOVE (OPEN)

 EXTERNAL SECONDARY GROOVE (CLOSED)

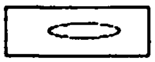
SUBSEQUENT SHAFT FEATURES



SHOWN EXTERNAL KEYWAY WITH RUNOUT

 EXTERNAL BLIND KEYWAY WITH RUNOUT

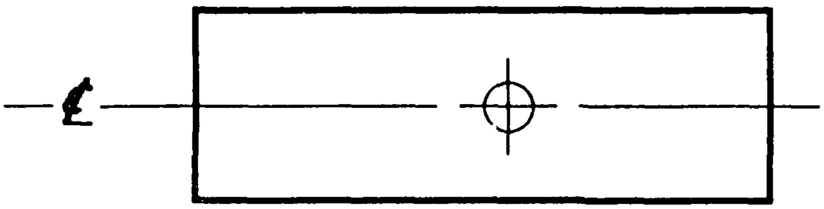
 EXTERNAL KEYWAY WITH RADIUS END

 EXTERNAL BLIND KEYWAY WITH RADUIS ENDS

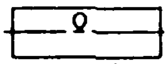
 EXTERNAL TRANSVERSE FLAT

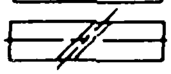
 3.6.6 EXTERNAL WOODRUFF KEYWAY

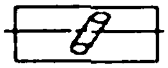
SUBSEQUENT SHAFT FEATURES



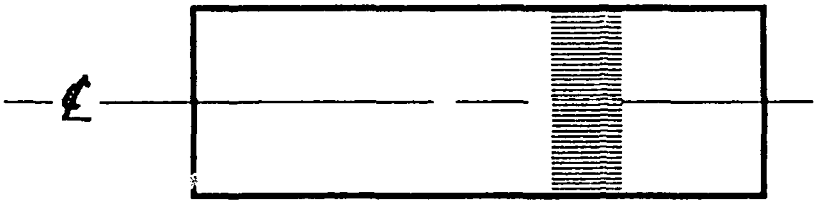
SHOWN CROSS DRILLED THRU CENTER

 CROSS DRILLED OFF CENTER

 OBLIQUE CROSS DRILLED THRU CENTER

 OBLIQUE CROSS DRILLED OFF CENTER

SUBSEQUENT SHAFT FEATURES



SHOWN

STRAIGHT KNURL (FINE)

STRAIGHT KNURL (MEDIUM)

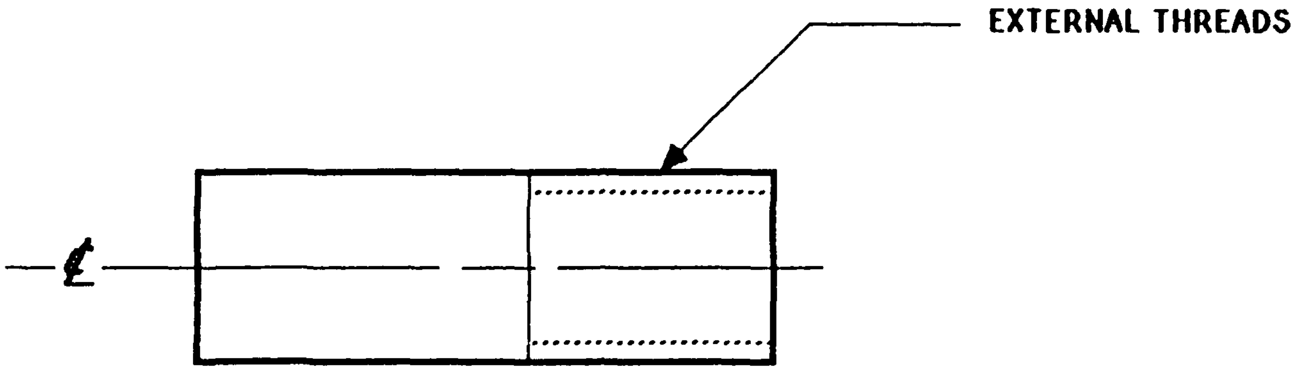
STRAIGHT KNURL (HEAVY)

DIAMOND KNURL (FINE)

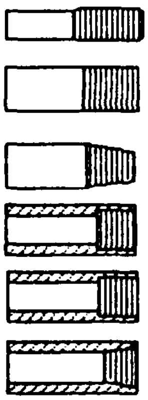
DIAMOND KNURL (MEDIUM)

DIAMOND KNURL (HEAVY)

SIMPLE SHAFT FEATURES



SHOWN EXTERNAL TURNED THREAD



EXTERNAL ROLLED THREAD

EXTERNAL DIE CUT THREAD

EXTERNAL TAPER THREAD

INTERNAL TURNED THREAD

INTERNAL TAPPED THREAD

INTERNAL TAPER THREAD

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APPENDIX C

REVIEW OF LOW COST ENGINEERING WORKSTATIONS.

The difference between personal computers, workstations, and minicomputers has become less and less distinct. A mini-computer which was purchased 4 to 5 years ago at a price of around $100,000 may not deliver computational power more than a workstation that only costs around $20,000 today. By the same token, an aging workstation may not be able to compete with a new 32-bit personal computers. The term "workstation" here is used to describe a small desktop computer with enough computer power to perform engineering applications. It can be a stand-alone system or a node on a local area network. The basic elements of a workstation which we considered for the DPAS project are:

- o Processing speed of .75 MIPS and up.
- o 32-bit technology hardware.
- o Use of a well-known multi-tasking operating system.
- o Support of LISP, "C", and FORTRAN.
- o Support of a wide range of knowledge engineering tools, graphics tools, databases, and manufacturing software.
- o Memory of at least 4 MByte.
- o Disk storage capacity of 75 Mbyte and up.
- o Networkable to a standard LAN, e.g., IEEE 802.3, IBM Token-Ring.
- o High resolution graphic.
- o Priced under $50,000.

APOLLO COMPUTER SERIES 3000. The new low-end Apollo Series 3000 workstation is based on a Motorola MC68020 processor operating at 16 MHz. with a MC688881 floating point co-processor. This workstation also has an IBM-AT compatible BUS. The larger capabilities from Apollo, the DN580 Turbo workstations are 2-D and 3-D color graphics workstations with higher resolution (1280x1024) and a drawing processor. Technical information about this system is given below:

Processor	MC68020, MC68881 at 16 MHz
Memory	Up to 8M
Buses	Multibus, IBM-AT
Mass storage	Up to 348 MB
Display resolution	1280x1024 or 1024x800
Operating system	Domain/IX, Aegis
Languages supported	Most programming languages
Applications	Over 600 with strength in graphics tools
LAN	DomainLAN
Protocols	TCP/IP, X.25, SNA
Pricing	$20,000-$40,000

Apollo computers are general purpose system with strength in graphics applications. Apollo supports most of the standard language compilers (e.g. C, FORTRAN, Pascal, LISP) and a wide range of graphics tool kits such as Graphics Kernel System (GKS), Programmer's Hierarchial Interactive Graphics System (PHIGS), and Graphics Metafile Resource (GMR).

The disadvantages of the Apollo system are:

- o Proprietary hardware and operating system (Domain/IX).
- o Proprietary LAN (DomainLAN).
- o Does not currently support IGES-formatted files.

COMPAQ COMPUTER COMPAQ DESKPRO 386/20. Under the definition of the DPAS workstation, the COMPAQ 386 can be classified as a high-end personal computer or a low-end workstation. The 386/20 is the second-generation version of the Deskpro 386 line and one of the best 80386-based machines available today. Though the speed of the 386 under DOS operating system may not be fast enough for large-scale CAD or expert system software, we expect a speed improvement a few times faster when it is operated under the 386 non-protected mode available with the O/S 2 from a few other software vendors. The weak areas of the workstation are lack of a company-supported LAN and high resolution graphics (at least at the IBM-VGA resolution of 720x400 text and 640x480 graphics or higher).

Processor	Intel 80386/20 MHz with either Intel 80387/20 MHz or Weitek WTL1167
Memory	Up to 16M
Buses	Proprietary 32-bit bus, IBM-AT 16-bit bus
Mass storage	Up to 300 MG
Display resolution	640x350 (EGA); Higher resolution available through 3rd party
Operating system	DOS 3.3 and O/S 2
Languages support	Most programming languages
Applications	Few thousand of DOS software
LAN	None; Ethernet, et.al.-3rd party
Protocols	XNS, TCP/IP-3rd party
Pricing	from $7,000

The disadvantages of Compaq 386/20 system are:

- o May not have enough processing power and memory under DOS.
- o Reliance on the new O/S 2 operating system (bugs are expected) for more power.
- o Reliance on third party support for both hardware and software development go become a "true" engineering graphics workstation.

DIGITAL EQUIPMENT CORPORATION VAXstation II, GPX. The VAXstation II/GPX is a general purpose workstation with a floating point unit and a graphics co-processor to speed up real number operations and graphics computations. The relative performance of the MVII/GPX is approximately 90% of the VAX-11/780. It is the first low cost, high-resolution color graphics computer offered by DEC. It uses a subset of the well-known VMS operating system which can run many of the DEC and third-party application programs for manufacturing such as MRP and CAD. Recently (4-Q of 87), DEC announced the third generation of the Micro-VAX workstation, the Micro-VAX 3500/3600. The 35xx system has 2.7 times processing power of the 11/780 and costs from $65,000.

Processor	Proprietary VSII
Memory	Up to 16M
Buses	Q-bus
Mass storage	Up to 477 MB (with BA123 enclosure)
Display resolution	1280x864
Operating system	Micro VMS, Ultrix-32
Languages supported	Most programming languages
Applications	Over 700 with strength in engineering
LAN	Decnet, Ethernet
Protocols	SNA, X.25
Pricing	$25,000-$65,000

The disadvantages of the Micro-VAX GPX system are:

- o Proprietary hardware and limited expandability.
- o More expensive for the same performance and configuration.

IBM PS/2 MODEL 80-111. The PS/2 Model 80 is the top-of-the-line machine for IBM's new line of personal computers. Implementation of the new Micro Channel bus architecture, the Intel 80386/20 MHz, and the number of 32-bit and 16-bit expansion slots offer good performance and good expandibility.

Processor	Intel 80386/20 MHz with Intel 80387/20 MHz
Memory	Up to 16M
Buses	Proprietary Micro Channel bus 3 32-but bus, 5 16-bit bus
Mass storage	Up to 115 MB (more through 3rd party)
Display resolution	1024x768
Operating system	DOS 3.3 and O/S 2
Languages supported	Most programming languages
Applications	Few thousand of DOS software Applications for O/S 2 are slowing coming

	LAN PC network broadband, PC network baseband Token-ring network 3rd party for Ethernet
Pricing	from $11,000

The disadvantages of IBM PS/2 Model 80-11 are:

- o May not have enough processing power and memory under DOS.
- o Reliance on the new O/S 2 operating system (bugs are expected) for more power.
- o Highest price of all the 80386-based machines.

SILICON GRAPHICS IRIS 3120. IRIS 3120 is a low cost graphics workstation from Silicon Graphics. IRIS 3120 uses the Motorola MC68020 as the main processor with a special graphics processor for graphics applications. The company is well known for its well-integrated graphics package which will do all CAD applications from 2-D wire frame drawings to solids modeling. For a super workstation, the IRIS top-of-the-line workstation, the IRIS-4D, is a RISC-based machine using semi-custom VLSI and has the speed of 5 to 7 MIPS.

Processor	MC68020/16 MHz
Memory	Up to 16M
Buses	Multibus
Mass storage	Up to 340 MG
Display resolution	1024x1024
Operating system	Unix System V
Languages supported	Most programming languages
Applications	Solids modeling, 3-D graphics many other graphics applications
LAN	Ethernet
Protocols	XNS, TCP/IP
Pricing	from $42,000

The disadvantages of the IRIS 3120 system are:

- o Lack of third-party hardware.
- o Lack of third-party software, especially software for manufacturing applications.
- o Not enough distributors for quality on-site services.

SUN MICROSYSTEMS SUN-3/60. The new Sun-3/60 Series is a low-cost 3 MIPS machine. It uses a 20 MHz Motorola MC68020, a 20 MHz MC68881 floating point co-processor, 4 MB of main memory, and 256 MB of virtual address. It provides one of the best price/performance workstations at this time and it comes in a very small box. The top-of-the-line, Sun-4/260 CXP, is a gra-

phics super-workstation based on RISC technology and has a processing speed of 10 MIPS.

Processor	MC68020/20 MHz with MC688881/20MHz
Memory	Up to 24M
Buses	No bus (A single board computer)
Mass storage	Up to 282 MB
Display resolution	1152x900 (color), 1600x1280 (mono)
Operating system	Converged UNIX (4.2 BSD and AT&T System V)
Languages supported	Most programming languages
Application	Few hundred including 3rd party software
LAN	Ethernet, NSF
Protocols	NSF, TCP/IP through Sun-Link: SNA, BSC, LU6.2, OSI and DECnet
Pricing	from $13,000

The disadvantages of Sun-3/60 system are:

- o No expansion
- o Not enough distributors for quality on-site services for some areas.

APPENDIX D

LIST OF ABBREVIATIONS

CAD	-	Computer Aided Design
CASE	-	Computer Assisted Software Engineering
CDM	-	Common Data Model
DPAS	-	Design Producibility Assessment System
EDA	-	Electrical Design Automation
EGA	-	Enhanced Graphics Adapter
ITS	-	Interactive Instruction System
MB	-	Mega Byte
MDA	-	Mechanical Design Automation
MI	-	Manufacturability Index
MIPS	-	Millions of Instructions Per Second
ODPD	-	Observed Design Production Difficulty
RAM	-	Random Access Memory
WPIF	-	Weighted Producibility Influencing Factor